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PROPERTIES OF WASTE BY-PRODUCTS FROM LIMESTONE (LIME) DUAL ALKALI AND LIMESTONE (LIME) WET SCRUBBING PROCESSES: A LITERATURE STUDY

Report No. 89-66-K

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ABSTRACT

The literature study was focused on the collection of physical and chemical properties of the waste by-products from the limestone (lime) dual alkali process and the limestone (lime) wet scrubbing process. Data on the untreated and stabilized (fixated) wastes were gathered to gain a better understanding of the properties/behaviour of these FGD wastes for the design and operation of a future Ontario Hydro solid waste management system, as well as for potential utilization/marketing options of these wastes. Brief discussions on the fixation processes for the FGD wastes and utilization cases of these stabilized wastes are included in the report.

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TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1-1
	REFERENCES	1-5
2.0	ENGINEERING CHARACTERISTICS OF UNTREATED FGD SLUDGES/FILTER CAKES GENERATED BY LIMESTONE (LIME) DUAL ALKALI AND LIMESTONE (LIME) SCRUBBING	2-1
	2.1 General	2-1
	2.2 Physical Properties	2-1
	2.2.1 General Description	2-1
	2.2.2 Mineralogy and Crystal Morphology	2-1
	2.2.3 Index properties	2-2
	2.2.3.1 Particle Size Distribution	2-2
	2.2.3.2 Specific Gravity	2-3
	2.2.3.3 Water Content	2-3
	2.2.3.4 Atterberg's Limits	2-4
	2.2.3.5 Solids Content	2-4
	2.2.3.6 pH	2-4
	2.2.4 Compaction Characteristics	2-4
	2.2.5 Shear Strength Characteristics	2-5
	2.2.6 Permeability	2-5
	2.2.7 Compressibility and Consolidation Characteristics	2-6
	REFERENCES	2-7
3.0	ENGINEERING CHARACTERISTICS OF STABILIZED LSDA SLUDGE/FILTER CAKE	3-1
	3.1 Physical and Chemical Properties of Laboratory Stabilized LSDA Sludge/Filter Cake	3-1
	3.1.1 General	3-1
	3.1.2 Properties of the Additives: Fly Ash and Lime	3-2
	3.1.2.1 Fly Ash	3-2
	3.1.2.2 Lime	3-2
	3.1.3 Physical and Chemical Properties of the Stabilized LSDA Sludge	3-2
	3.1.3.1 Index Properties of the Stabilized LSDA Sludge	3-3
	3.1.3.2 Compaction Characteristics	3-3
	3.1.3.3 Shear Strength Characteristics	3-4

TABLE OF CONTENTS (Cont'd)

		Page
3.1.3.3.1	Isotropically Consolidated Drained Triaxial Tests	3-4
3.1.3.3.2	Unconfined Compression Tests	3-6
3.1.3.4	Permeability	3-9
3.1.3.4.1	Effect of Curing Time	3-9
3.1.3.4.2	Effect of Lime Content	3-9
3.1.3.4.3	Effect of Solids Content	3-9
3.1.3.4.4	Effect of Compaction	3-10
3.1.3.5	Compressibility and Consolidation Characteristics	3-10
3.1.3.5.1	Compressibility Characteristics	3-10
3.1.3.5.2	Consolidation Characteristics	3-10
3.2	Physical and Chemical Properties of Pond Mix Stabilized LSDA Sludge	3-11
3.2.1	General	3-11
3.2.2	Index Properties	3-11
3.2.3	Shear Strength Characteristics	3-11
3.2.3.1	Isotropically Consolidated Drained Triaxial Tests	3-11
3.2.3.2	Unconfined Compression Tests	3-12
3.2.4	Permeability	3-12
REFERENCES		3-13
4.0	ENGINEERING CHARACTERISTICS OF STABILIZED LDA SLUDGE/FILTER CAKE	4-1
4.1	General	4-1
4.2	Physical Properties	4-1
4.2.1	Mineralogy and Composition	4-1
4.2.2	Index Properties	4-2
4.2.2.1	Particle Size Distribution	4-2
4.2.2.2	Specific Gravity	4-2
4.2.2.3	Water Content	4-2
4.2.2.4	Atterberg's Limits	4-2
4.2.2.5	pH	4-2

TABLE OF CONTENTS (Cont'd)

		Page
4.2.3	Compaction Characteristics	4-3
4.2.4	Shear Strength Characteristics	4-3
4.2.4.1	Consolidated Drained and Undrained Triaxial Tests	4-3
4.2.4.2	Unconfined Compression Tests	4-4
4.2.4.3	Load Bearing Test	4-4
4.2.5	Permeability	4-5
4.2.6	Compressibility and Consolidation Characteristics	4-5
4.2.6.1	Compressibility	4-5
4.2.6.2	Consolidation Characteristics	4-5
REFERENCES		4-7
5.0	ENGINEERING CHARACTERISTICS OF STABILIZED LIMESTONE WET SCRUBBER SLUDGE/FILTER CAKE	5-1
5.1	General	5-1
5.2	Physical Properties of Treated LSWS Sludge	5-1
5.2.1	Mineralogy and Composition	5-1
5.2.2	Index Properties	5-1
5.2.2.1	Particle Size Distribution	5-1
5.2.2.2	Specific Gravity	5-2
5.2.2.3	Water and Solids Content	5-2
5.2.3	Compaction Characteristics	5-2
5.2.4	Shear Strength Characteristics	5-3
5.2.4.1	Triaxial Compression Test	5-3
5.2.4.2	Unconfined Compression Test	5-3
5.2.4.3	Load Bearing Test	5-4
5.2.5	Permeability	5-4
5.2.6	Compressibility and Consolidation Characteristics	5-4
REFERENCES		5-6
6.0	CHEMICAL COMPOSITION AND LEACHATE ANALYSIS OF FGD SLUDGES GENERATED FROM LSDA, LDA AND LWS PROCESSES	6-1
6.1	General	6-1
6.2	Chemical Composition and Leachate Analysis of LSDA Sludge	6-1
6.3	Chemical Composition and Leachate Analysis of LDA Sludge	6-2
6.4	Chemical Composition and Leachate Analysis of LWS Sludge	6-3
REFERENCES		6-4

TABLE OF CONTENTS (Cont'd)

		Page
7.0	COMMERCIAL FIXATION PROCESS	7-1
	7.1 IU Conversion Systems (IUCS) Poz-O-Tec Process	7-1
	7.1.1 Process Description	7-1
	7.1.2 Properties of Stabilized Sludge	7-2
	7.1.3 Case Histories	7-2
	7.2 Dravo Process Using Calcilox	7-2
	7.2.1 Process Description	7-2
	7.2.2 Applicability of Dravo Process Technology	7-3
	7.2.3 Properties of Stabilized Sludge	7-3
	7.2.4 Case Histories	7-3
	7.3 Chemfix Process	7-3
	7.3.1 Process Description	7-3
	7.3.2 Applicability of the Chemfix Process	7-4
	7.3.3 Properties of the Stabilized Sludge	7-4
	7.3.4 Case Histories	7-4
	7.4 Forced Oxidation	7-4
	7.4.1 Process Description	7-4
	7.4.2 Properties of the Stabilized Sludge	7-4
	7.4.3 Case Histories	7-5
	REFERENCES	7-6
8.0	UTILIZATION OPTIONS	8-1
	REFERENCES	8-4
9.0	RECOMMENDATIONS FOR FUTURE RESEARCH	9-1
	9.1 General	9-1
	9.2 Recommendations for Future Research	9-1
	REFERENCES	9-3
10.0	ACKNOWLEDGEMENTS	10-1
	DISTRIBUTION	last page

LIST OF TABLES

		Page
2-1	MINERALOGY OF UNTREATED FGD SLUDGES	2-8
2-2	SPECIFIC GRAVITY AND LIQUID LIMIT OF UNTREATED FGD SLUDGES	2-9
2-3	WATER CONTENT OF UNTREATED FGD SLUDGES	2-10
2-4	SOLIDS CONTENT OF UNTREATED FGD SLUDGES	2-11
2-5	COMPACTION CHARACTERISTICS OF UNTREATED FGD SLUDGES	2-12
2-6	COMPACTION CHARACTERISTICS OF LSDA SLUDGE OBTAINED FROM DIFFERENT PERIODS	2-13
2-7	SHEAR STRENGTH PARAMETERS OF UNTREATED FGD SLUDGES	2-14
2-8	PERMEABILITY OF UNTREATED FGD SLUDGES	2-15
2-9	PERMEABILITIES OF UNSTABILIZED FGD SLUDGES	2-16
3-1	INDEX PROPERTIES OF FILTER CAKE, FLY ASH, LIME & POND MIX STABILIZED FGD SLUDGE FOR THE LSDA PROCESS AT PLANT SCHOLZ	3-14
3-2	INDEX PROPERTIES OF LABORATORY MIX STABILIZED LSDA SLUDGE FROM PLANT SCHOLZ	3-15
3-3	COMPARISON OF DRY DENSITIES OF STABILIZED LSDA SLUDGE AT NATURAL WATER CONTENT & OPTIMUM WATER CONTENT	3-16
3-4	SUMMARY OF MOHR-COULOMB EFFECTIVE STRESS STRENGTH PARAMETERS FOR CURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ)	3-17
3-5	SUMMARY OF UNTREATED AND TREATED LSDA SLUDGE	3-18
4-1	REPORTED MINERALOGY OF TYPICAL LDA SLUDGE	4-8
4-2	INDEX PROPERTIES OF STABILIZED LDA SLUDGE	4-9
4-3	MAXIMUM DRY DENSITY AND OPTIMUM WATER CONTENT OF STABILIZED LDA SLUDGE	4-10
4-4	SHEAR STRENGTH CHARACTERISTICS OF STABILIZED LDA SLUDGE	4-11
4-5	UNCONFINED COMPRESSION TEST ON STABILIZED LDA SLUDGE	4-12
4-6	COEFFICIENT OF PERMEABILITY OF STABILIZED LDA SLUDGE	4-13
4-7	COMPRESSION INDICES OF STABILIZED LDA SLUDGE	4-14

LIST OF TABLES (Cont'd)

		Page
5-1	MIX CONSISTENCIES WITH VARIOUS ADDITIVES FOR LAKEVIEW GS SCRUBBER LSWS SLUDGE WITH 65% SOLIDS	5-7
5-2	RESULTS OF COMPACTION TEST FOR LSWS SLUDGES AND SLUDGE/FLY ASH MIXTURES	5-8
5-3	CONSOLIDATED UNDRAINED TRIAXIAL TESTS OF LSWS SLUDGE/LOW ALKALI ASH MIXTURES	5-9
5-4	SHEAR STRENGTH CHARACTERISTICS OF STABILIZED LIMESTONE SCRUBBING SLUDGE	5-10
5-5	SLUDGE STABILIZATION TESTS	5-11
5-6	UNCONFINED COMPRESSIVE STRENGTH (Kg/Cm^2) OF LSWS SLUDGE/LOW ALKALI ASH MIXTURES	5-12
5-7	UNCONFINED COMPRESSIVE STRENGTH (Kg/Cm^2) OF LSWS SLUDGE/HIGH ALKALI ASH MIXTURES	5-13
5-8	COEFFICIENTS OF PERMEABILITY OF STABILIZED LSWS SLUDGE	5-14
6-1	ENVIRONMENTAL OBJECTIVES RELATED TO WASTEWATER DISCHARGES IN NORTH AMERICA	6-5
6-2	CHEMICAL COMPOSITION OF LSDA SLUDGE LIQUORS	6-6
6-3	PEAK & STEADY STATE LEACHATE CONSTITUENT CONCENTRATIONS FROM LSDA SLUDGE	6-7
6-4	TRACE ELEMENT ANALYSIS FOR SCHOLZ LEACHATE & FIELD-WORTHY SAMPLE OF LSDA SLUDGE	6-8
6-5	CHEMICAL ANALYSIS OF FMC LDA SLUDGE (FMC, 1987)	6-9
6-6	LEACHATE ANAYSIS OF LDA SLUDGE (SCHAHFER STATION)	6-10
6-7	CHEMICAL ANALYSIS OF LWS SLUDGES USING COMMERCIAL LIME & CARBIDE LIME	6-11
6-8	LABORATORY LEACHATE ANALYSES OF LWS SLUDGE	6-12
7-1	RESULTS OF TESTS OF SELECTED STABILIZED ROAD BASE MIXTURES PREPARED AT DULLES AIRPORT TRANSPO 72 PROJECT	7-7
7-2	FLUE GAS CLEANING WASTES DISPOSAL PROJECTS CONTRACTED BY I.U. CONVERSION SYSTEMS	7-8
7-3	FLUE GAS CLEANING WASTE DISPOSAL PROJECTS CONTRACTED BY DRAVO CORPORATION	7-9

LIST OF FIGURES

		Page
1-1	LIMESTONE DUAL ALKALI PROCESS	1-6
1-2	MASS BALANCE WET LIMESTONE SCRUBBING	1-7
2-1	PARTICLE SIZE DISTRIBUTION OF UNTREATED FGD FILTER CAKE (LSDA PROCESS)	2-17
2-2	APPARENT WATER CONTENT VERSUS DRYING TEMPERATURE FOR A LSDA FILTER CAKE FROM PLANT SCHOLZ	2-18
2-3	BULK DENSITY AS A FUNCTION OF SOLIDS CONTENT: TVA SHAWNEE LWS SLUDGE WITHOUT STABILIZATION	2-19
2-4	COMPACTION CURVES FOR UNTREATED FGD SLUDGES	2-20
2-5	TYPICAL MOHR-COULOMB PARAMETERS FOR FGD SULFITE SLUDGES	2-21
2-6	VOID RATIO VERSUS COEFFICIENT OF PERMEABILITY FOR SULFITE FGD SLUDGES	2-22
2-7	SOLIDS CONTENT VERSUS COEFFICIENT OF PERMEABILITY OF TREATED AND UNTREATED FGD FILTER CAKE	2-23
2-8	COMPRESSIBILITY CHARACTERISTICS OF UNTREATED FGD SULFITE SLUDGES	2-24
2-9	TYPICAL VOID RATIO VERSUS TIME CONSOLIDATION CURVES FOR A LSDA FILTER CAKE FROM PLANT SCHOLZ	2-25
3-1	PARTICLE SIZE DISTRIBUTION OF STABILIZED LSDA SLUDGE WITH S_c=47% AND L=3.0%	3-20
3-2	PARTICLE SIZE DISTRIBUTION OF STABILIZED LSDA SLUDGE WITH S_c=56% AND L=3.0%	3-21
3-3	MOISTURE CONTENT VS LIME CONTENT	3-22
3-4	MOLDING WATER CONTENT VERSUS DRY DENSITY FOR 100 psi STATIC COMPACTION EFFORT - LSDA SLUDGE FROM PLANT SCHOLZ	3-23
3-5	COMPARISON OF MOHR-COULOMB PARAMETERS FOR CURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ) WITH S_c=56%, R=0.75 AND L=1.0, 3.0 AND 5.0%	3-24
3-6	EFFECT OF LIME CONTENT ON EFFECTIVE COHESION AND FRICTION ANGLE OF CURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ)	3-25

LIST OF FIGURES CONT'D

		Page
3-7	C' AND 0' VS SOLIDS CONTENT OF STABILIZED LSDA SLUDGE (PLANT SCHOLZ)	3-26
3-8	EFFECT OF LIME CONTENT AND WIRING ENVIRONMENT ON UNCONFINED COMPRESSIVE STRENGTH OF CURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ)	3-27
3-9	LIME CONTENT VS TIME REQUIRED TO DEVELOP MAXIMUM UNCONFINED COMPRESSION STRENGTH OF STABILIZED LSDA SLUDGE (PLANT SCHOLZ)	3-28
3-10	EFFECT OF CURING TIME ON COEFFICIENT OF PERMEABILITY OF STABILIZED LSDA SLUDGE (PLANT SCHOLZ)	3-29
3-11	TYPICAL VOID RATIO VERSUS TIME CONSOLIDATION CURVES FOR UNCURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ) WITH S_c=47%, R=0.75 and L=3.0%	3-30
3-12	UNDRAINED STRESS-STRAIN BEHAVIOUR OF CURED POND MIX STABILIZED LSDA SLUDGE (PLANT SCHOLZ)	3-31
3-13	UNDRAINED EFFECTIVE STRESS PATHS AND MOHR-COULOMB PARAMETERS FOR CURED POND MIX STABILIZED LSDA SLUDGE (PLANT SCHOLZ)	3-32
4-1	PARTICLE SIZE DISTRIBUTION OF DOUBLE ALKALI SLUDGES	4-15
4-2	COMPACTION CHARACTERISTICS OF LDA SLUDGES	4-16
4-3	EFFECT OF FLY ASH ON UNCONFINED COMPRESSIVE STRENGTH OF LDA SLUDGES	4-17
4-4	EFFECT OF LIME ON UNCONFINED COMPRESSIVE STRENGTH OF LDA SLUDGE-FLY ASH MIXTURES	4-18
4-5	UNCONFINED COMPRESSIVE STRENGTH OF LDA SLUDGES	4-19
4-6	LOAD-BEARING STRENGTH OF LDA SLUDGE AS A FUNCTION OF MOISTURE, FLY ASH, AND SLUDGE ORIGIN	4-20
4-7	PERMEABILITY OF LDA SLUDGES AND SLUDGE-FLY ASH MIXTURES	4-21
4-8	CONSOLIDATION CURVES FOR LDA SLUDGES	4-22
4-9	CONSOLIDATION CURVES OF LDA SLUDGE	4-23
5-1	PARTICLE SIZE DISTRIBUTION OF LSWS SLUDGE	5-15

LIST OF FIGURES CONT'D

		Page
5-2	PARTICLE SIZE DISTRIBUTION CURVES FOR UNTREATED LSWS SLUDGE AND FLY ASH	5-16
5-3	CONSISTENCY OF 65% SOLIDS SLUDGE AND CONDITION OF LSWS SPECIMENS OF VARIOUS MIXTURES AFTER MOLDING	5-17
5-4	EFFECTIVE STRESS PARAMETERS FOR TREATED LSWS SLUDGE SPECIMENS FROM A CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION TEST	5-18
5-5	DRY DENSITY VERSUS ANGLE OF INTERNAL FRICTION OF LSWS SLUDGE	5-19
5-6	RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND CURING TIME FOR LSWS SLUDGE TREATED WITH FLY ASH	5-20
5-7	RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND CURING TIME FOR LSWS SLUDGE TREATED WITH CEMENT	5-21
5-8	RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND CURING TIME FOR LSWS SLUDGE TREATED WITH FLY ASH AND CEMENT	5-22
5-9	RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND CURING TIME FOR LSWS SLUDGE TREATED WITH FLY ASH AND QUICKLIME	5-23
5-10	LOAD-BEARING STRENGTH OF LSWS SLUDGES AS A FUNCTION OF SOLIDS CONTENT	5-24
5-11	VOID RATIO VERSUS COEFFICIENT OF PERMEABILITY OF LSWS SLUDGE	5-25
5-12	VOID RATIO VERSUS EFFECTIVE STRESS COMPRESSIBILITY CURVE OF LSWS SLUDGE	5-26
6-1	CONCENTRATION OF MAJOR SPECIES AND TDS IN LEACHATE OF LDA SLUDGE WITH AND WITHOUT FLY ASH: GPC PLANT SCHOLZ	6-13
6-2	CONCENTRATION OF MAJOR SPECIES AND TDS IN LEACHATE ANALYSIS OF LWS SLUDGE WITH AND WITHOUT FLY ASH: TVA SHAWNEE, RUN F	6-14
7-1	AVERAGE STRENGTH OF 26 LIME-SULFATE-FLY ASH-AGGREGATE MIXTURES	7-10
7-2	FORCED OXIDATION	7-11
8-1	SCHEME FOR PRODUCING SUITABLE LAND FILL	8-5

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Attn: Mr. J.C. Flynn

PROPERTIES OF WASTE BY-PRODUCTS FROM LIMESTONE (LIME) DUAL ALKALI AND LIMESTONE (LIME) WET SCRUBBING PROCESSES: A LITERATURE STUDY

1.0 INTRODUCTION

Ontario Hydro is committed to providing electricity to the people of Ontario while ensuring that the environment is well protected. Specifically, in dealing with the acid rain problems, the Corporation has several long-term options available to control the acid gas emissions from its several coal-fired generation stations. One of the options being seriously considered is to retrofit some of the coal-fired generating stations with flue gas desulphurization (FGD) facilities. From the result of a technical and economic evaluation of commercially available FGD technologies, the Corporation would decide to equip one or more of the following FGD technologies at selected coal-fired stations:

(1) limestone dual alkali
(2) limestone slurry
(3) lime spray dryer, or
(4) furnace injection

The first two processes are the "wet" processes in which the sludge/filter cake is the FGD waste by-product. The third and fourth processes are the "dry" processes in which the FGD wastes contain only a small quantity of moisture.

To ensure that these FGD wastes are disposed of in an environmentally acceptable manner and, to gain a better understanding of the properties/behaviour of these materials so that a marketing strategy can be formulated for these by-products (as produced or stabilized), Mr. J.C. Flynn of the Supply Division requested the Civil Research staff to collect from the literature available data pertaining to these wastes.

Because of budget and time constraints, the study was limited only to the limestone slurry process and the limestone dual alkali process.

The study will consist of several parts:

(1) Brief description of the limestone (lime) dual alkali process and the limestone (lime) wet slurry process.

(2) Collection of engineering properties and chemical properties of untreated sludges/filter cakes produced by these two processes.

(3) Collection of engineering properties and chemical properties of stabilized (or treated) sludges/filter cakes produced by these two processes.

(4) Brief discussion of some fixation processes.

(5) Utilization options and some brief case records.

It should be pointed out that an understanding of the engineering properties/behaviour of the FGD wastes is useful for the design and operation of a solid waste management system, as well as for considering potential utilization options for the FGD solid wastes. Specifically, the data collected can provide information necessary to:

- predict the behaviour of the wastes during handling, storage, transport and disposal.
- establish operational guidelines and design criteria on the handling, storage, transport and disposal of the wastes.
- estimate the quantity and quality of both leachate and surface run-off, and
- evaluate potential utilization options.

In the following paragraphs, the limestone (lime) dual alkali (LSDA) and limestone wet slurry (LSWS) processes are briefly described.

In the lime dual alkali (LDA) process, Na_2CO_3 serves as the primary absorbent and lime is added to regenerate sodium sulfite from sodium bisulfite (Summers et al, 1983). The limestone dual alkali (LSDA) process is a development of the lime dual alkali process; the difference being that limestone, rather than lime, serves as the scrubbing reagent. Since limestone is less expensive than lime, it is economically more attractive.

The flue gas passes through the absorption section where sulfur dioxide, sulfur trioxide, and trace gases, such as chlorides, are removed via contact with the absorbent. In the LDA process, the resulting solution is reacted with hydrated lime to regenerate the scrubbing solution and produce calcium sulfite and/or calcium sulfate as solid wastes. In the LSDA process, limestone is used to replace lime and the solid wastes produced also contain unreacted limestone. In either process, the solid wastes are separated from the regenerated scrubbing solution through settling or filtration and are removed for stock piling or landfilling. The regenerated scrubbing solution

is recirculated to the absorption section for further sulfur dioxide removal (Rush and Edwards, 1978). The mass flow diagram of the limestone dual alkali process is shown in Figure 1-1.

The process chemistry is described briefly. Sulfur dioxide is removed by reacting with the original absorbent-sodium carbonate, as shown in the following reactions:

$$Na_2CO_3 + SO_2 \rightarrow Na_2SO_3 + CO_2 \quad (1)$$

$$2NaOH + SO_2 \rightarrow Na_2SO_3 + H_2O \quad (2)$$

$$Na_2SO_3 + SO_2 + H_2O \rightarrow 2NaHSO_3 \quad (3)$$

Absorption of sulfur dioxide also takes place when sulfur dioxide reacts with the recycled scrubbing solution which contains sodium sulfite to form sodium bisulfite according to reaction (3). An appropriate quantity of sodium carbonate will be added to the system to make up for the loss of sodium sulfite depending on the extent of regeneration of absorbent.

In the lime dual alkali process, the regeneration of sodium sulfite from sodium bisulfite can be simplified by the following reaction (Rush and Edwards, 1978):

$$2NaHSO_3 + Ca(OH)_2 \rightarrow Na_2SO_3 + CaSO_3.1/2\ H_2O + 3/2\ H_2O \quad (4)$$

In the limestone dual alkali process, the sodium bisulfite reacts with calcium carbonate of the limestone to regenerate sodium sulfite as follows (Ontario Hydro, 1987):

$$2NaHSO_3 + CaCO_3 \rightarrow Na_2SO_3 + CaSO_3.1/2\ H_2O + CO_2 + 1/2\ H_2O \quad (5)$$

The insoluble calcium salts, mostly calcium sulfite hemi-hydrate, are removed from the liquid by settling in a thickener.

In the limestone wet scrubbing (LSWS) process, the flue gases are reacted with a thin slurry of crushed limestone. The contact chamber may be of the venturi-spray, packed-tower, mobile-bed or simple spray-tower type. The slurry circulates between the contact chamber and a separated reaction tank, to which the reagents are added. A bleed of lime from the reaction tank leads to a sludge thickening/dewatering device. Supernatant from the dewatering process is recycled to the reaction tank, and the remaining sludge, containing 40-60 percent by weight of solids, is removed for stock piling or disposal (Summers et al, 1983). The mass flow diagram of the limestone wet scrubbing process is presented in Figure 1-2.

Sulfur dioxide removal typically takes place in the vertical absorber where limestone slurry is sprayed into the flue gas. The reactions describing the process can be simplified as shown below:

$$SO_2 + 1/2\ H_2O + CaCO_3 \rightarrow CaSO_3.1/2\ H_2O + CO_2 \quad (6)$$

$$CaCO_3 + SO_2 + 2H_2O + 1/2\ O_2 \rightarrow CaSO_4.2H_2O + CO_2 \quad (7)$$

Efficiency of the sulfur dioxide removal can be enhanced by addition of an organic acid, such as dibasic, formic or adipic acid, to the reagent slurry (Ontario Hydro, 1987).

This report is organized as follows:

Chapter 1 provides a general introduction of this study and briefly describes the limestone (lime) dual alkali and the limestone (lime) scrubbing processes.

Presented in Chapter 2 is the engineering properties of untreated sludges/filter cakes generated by the dual alkali and the wet scrubbing processes.

Chapters 3, 4, and 5 summarize the engineering properties of stabilized sludges/filter cakes generated by the LSDA, LDA and LSWS processes, respectively.

Chemical properties of the wastes generated by the dual alkali and the wet scrubbing processes are summarized in Chapter 6.

Chapters 7 and 8 describe respectively some commercially available fixation technologies on FGD sludges and utilization options of the waste.

Recommendations for further researches are given in Chapter 9.

CHAPTER 1

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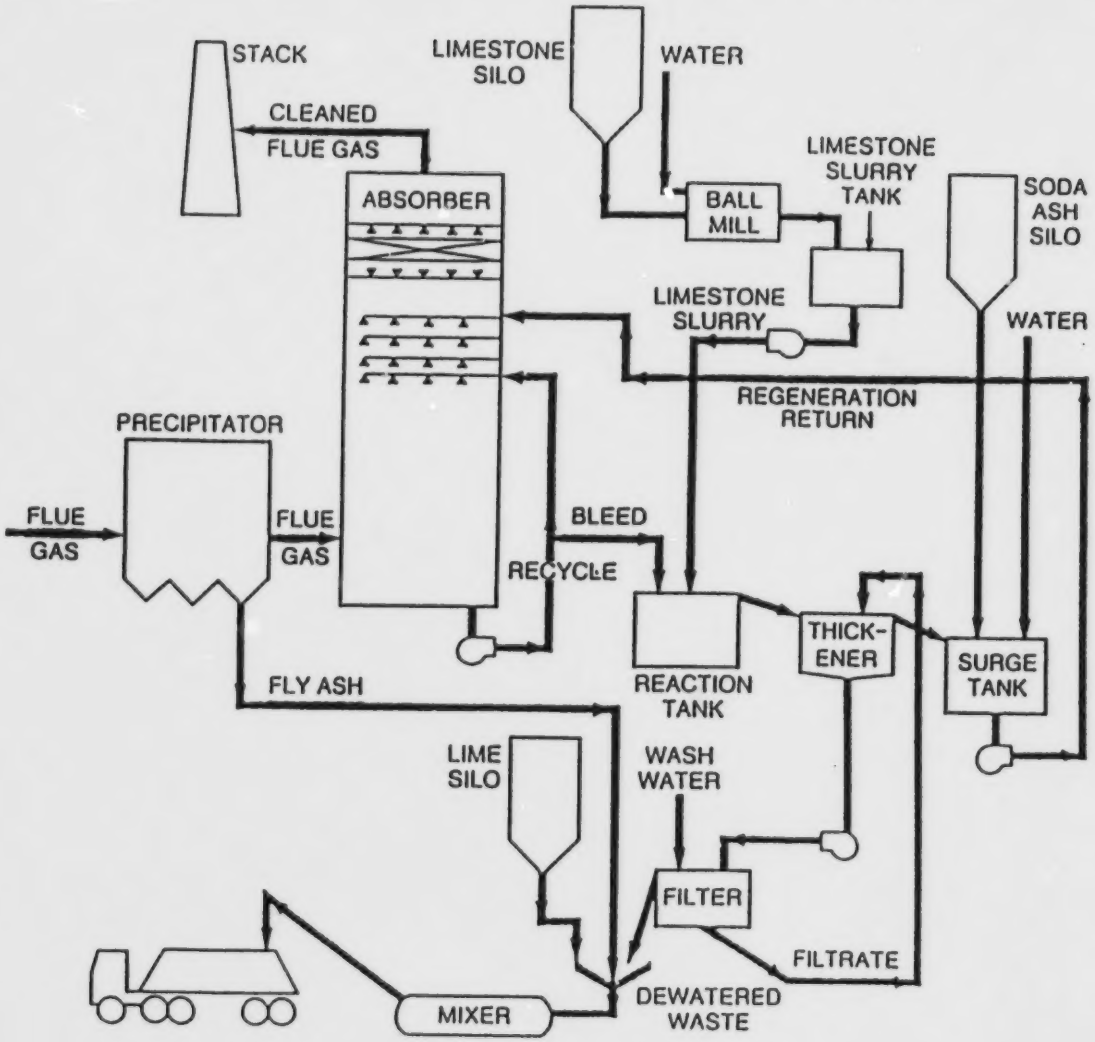

FIGURE 1-1

LIMESTONE DUAL ALKALI PROCESS
(ONTARIO HYDRO, 1987)

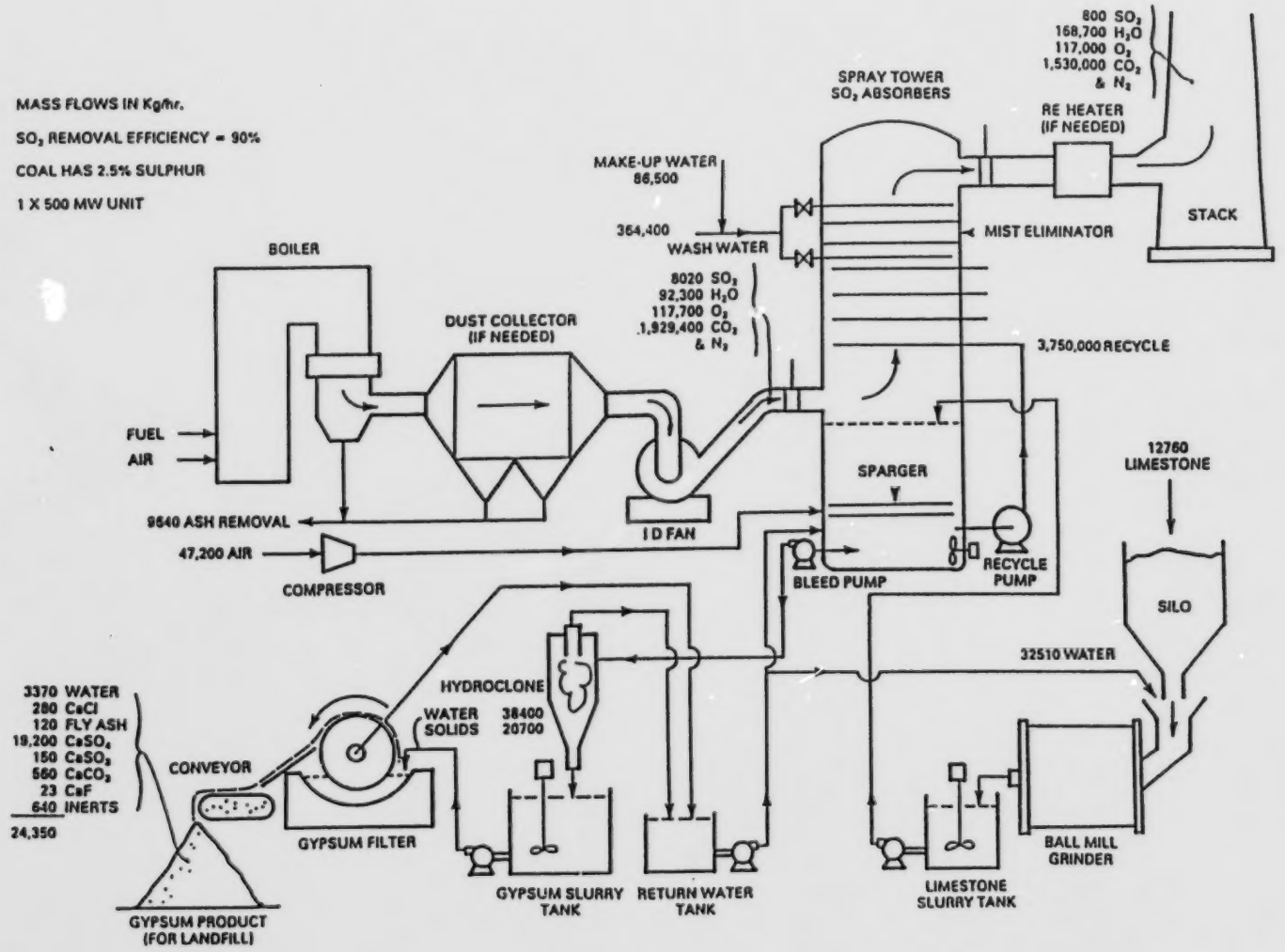

FIGURE 1-2

MASS BALANCE WET LIMESTONE SCRUBBING
(ONTARIO HYDRO, 1987)

2.0 ENGINEERING CHARACTERISTICS OF UNTREATED FGD SLUDGES/FILTER CAKES GENERATED BY LIMESTONE (LIME) DUAL ALKALI AND LIMESTONE (LIME) SCRUBBING

2.1 General

The untreated FGD sludges are those materials collected directly from the thickener without passing through any dewatering process whereas untreated FGD filter cakes are referred to those sludges whose water contents have been reduced by either vacuum filtering, centrifugal dewatering or other mechanical processes.

The engineering behaviour of FGD sludges/filter cakes produced from the L.S. Wet Scrubbing and LDA/LSDA is governed by their physical and chemical properties. The physical properties that are important to engineers include crystal morphology, specific gravity, grain-size distribution, water content, solids content, bulk density, Atterberg limits, compaction characteristics, compressibility and consolidation characteristics, shear strength, permeability, viscosity, dehydration and thixotropic behaviour. The chemical properties include chemical composition, pH, dehydration, and leachate quality.

The composition of FGD wastes vary considerably with the sulphur content of the coal, the technology employed by the desulphurization process and the sorbent used.

In the following discussion, the term FGD sludges/filter cakes are pertaining to those sludges/filter cakes generated by limestone (lime) dual alkali and limestone (lime) wet scrubbing processes.

It is attempted in this chapter to summarize all the available data on the engineering characteristics of the untreated FGD sludges generated by the LS(L)DA and LS(L)WS processes and to recommend effective solutions on their disposal and utilization.

2.2 Physical Properties

2.2.1 General Description

The as-produced FGD sludges are, in general, composed of very fine-grained, light greyish yellow to yellowish white, highly compressible materials with very high water content. The amount of water content varies according to the dewatering methods used, but is generally higher than their liquid limits.

2.2.2 Mineralogy and Crystal Morphology

Engineering properties of FGD sludges are fundamentally related to their mineralogy and chemical composition. The morphology, that is the size, shape, and complexity, of the solids component of the sludge determines the bulk slurry properties such as settling and filtration rates, pumpability, and ultimately dewatering (Seale, 1979).

In general, FGD sludges contain a mixture of calcium sulfate, calcium sulfite, fly ash, unreacted lime or limestone, and a number of trace elements such as arsenic, cadmium, iron, copper and other elements (Hagerty et al, 1977). The sludges produced by the dual alkali process also contain soluble sodium sulfate and sulfite salts and chloride salts (Krizek, 1979). The relative amount of each of the solid crystalline phase depends upon the sulphur content of the coal, the efficiency of the scrubbing process, the amount of fly ash in the flue-gas passing through the scrubbing and the efficiency of the system to remove fly ash, the stoichiometric ratio of reactants added relative to sulfur content and the reactant utilization efficiency (Rossoff et al, 1979). The relative amount of major crystals present in the sludge produced from various FGD process are presented in Table 2-1.

The calcium sulfite crystals which resemble the size and properties of non-plastic silts are generally smaller than the calcium sulfate crystals. Sulfite crystals are typically of 0.5 μm to 2.0 μm in thickness and 2 μm to 40 μm in length whereas sulfate crystals are larger, and are often cubic in shape.

Calcium sulfite crystals occur typically in the form of clusters and each cluster may contain 5 to 100 or more plastes. Calcium sulfate generally grows in single or twin crystals and is usually blocky in structure.

The ratio of sulfate to sulfite in FGD system is important because of the differences in crystal quantity and shape. These differences become a determining factor particularly in dewatering because sulfates are more easily dewatered. As the relative quantity of the sulfates increases, the solids content of dewatered sludge also increases (Coltharp et al, 1979).

The morphology and size of the crystals formed depend on the type of sorbent and the type of the boiler and gas cleaning equipment.

The crystalline morphology of sludges generated by both lime and limestone dual alkali processes were largely individual needles and has a leafy rosette structure (Fox et al, 1982 and FMC, 1987) whereas the morphology of the sludge generated by the wet scrubbing process had a platelet-like structure as typically reported for sulfite sludge (Hagerty et al, 1977). The differences in the form in which the sulfite was found in different processes was attributed to differences in precipitation and growth rates.

In the wet scrubbing system, sulfite crystallized predominately as a well-formed single plate when limestone was used as the sorbent, and appeared as spherical, closely interpenetrating aggregates when lime was used (Coltharp et al, 1979).

2.2.3 Index Properties

2.2.3.1 Particle Size Distribution

The particle size distribution of a sludge has major influence on its density, compaction characteristics and permeability.

Calcium sulfite is a silt-size material whereas calcium sulfate is of fine sand (Hagerty et al, 1977). Both crystals are fairly uniform in size. Presented in Figure (2-1) is the particle size distribution of typical sulfite sludge.

The small silt-size sulfites are difficult to be dewatered just by sedimentation. They can be vacuum filtered to a solids content of 50% whereas sulfates can be vacuum filtered to a solids content of 80% to 85% (Hagerty et al, 1977).

2.2.3.2 Specific Gravity

Specific gravity is defined as the ratio of the unit weight of the solid to the unit weight of water.

The specific gravity of various sludge are given in Table 2-2.

The sulfate-riched sludges have lower value of specific gravity than the sulfite-riched sludge.

2.2.3.3 Water content

Water content is defined as the weight of water to the weight of dry solids. Sludge handling and compaction are highly dependent on the water content of the sludge.

The water content of FGD sludges are generally high and are dependent on the dewatering methods as shown in Table 2-3. It can be seen that vacuum filtering and centrifugal dewatering can reduce the water content by about 10% to 50%.

Krizek et al, (1987) pointed out that the drying temperature used in determining the water content of FGD sludges may have significant effect on the measured values. The variation of the measured water content with drying temperature is shown in Figure 2-2 (Fox et al, 1982). It can be seen that the measured water content increases suddenly when the drying temperature is above 80 degrees. The drying temperature has a more significant effect on sulfate-hydrate riched sludge because, at high temperature, the chemically bonded water of the calcium sulfate dehydrate ($CaSO4.2H_20$) will be released. Drying temperature has less effect on determining the water content of sulfite rich sludge.

Klym and Dodd, (1974) reported that if a FGD sludge was dewatered to about 74% solids content, it would be firm enough to be compacted. A typical centrifugal or thickener vacuum filtered combination could manage to dewater the sludge to 65% of solids content but it was proved to be extremely difficult to go beyond 65% (Klym and Dodd, 1974).

2.2.3.4 Atterberg's Limits

Liquid limit is defined as the water content above which the material will behave like a viscous liquid; whereas plastic limit is defined as the water content below which the material will behave plastically.

Krizek, (1979) and Hagerty et al, (1977) pointed out that most FGD sludges that they had tested were non-plastic. The water content of various FGD sludges obtained from different dewatering methods are presented in Table 2-3. Note that the natural water content of the filter cakes are higher than the liquid limits shown in Table 2-2. The sludges can therefore be described as unstable solids and they have to be stabilized so that a proper handling and disposal operation can be implemented.

2.2.3.5 Solids Content

Solids content is defined as the weight of dry solid to the total (solid and water) weight of the material. It can be related to the water content (Mc) by the following formula:

$$\text{Solids content (Sc)} = \frac{1}{Mc+1}$$

Similar to the water content, the solids content of the sludge depends on the dewatering process employed in obtaining the sludge as shown in Table 2-4. Vacuum filtering and centrifugal dewatering can produce sludges that have higher solids content and less water content. Rossoff et al, (1979) showed that the bulk density of typical sulfite sludge increased with the amount of solids content as shown in Figure 2-3.

2.2.3.6 pH

The pH of as-produced FGD sludges depends on the quality of the coals, the pH level of the process and the sorbent used. The pH of untreated sludges generated from LDA, LWS and LSWS processes were reported to be alkaline or neutral (Rush and Edwards, 1978 and Coltharp et al, 1979) whereas the pH of untreated LSDA sludge was reported to range from 4.3 to 4.5 (Fox et al, 1982).

2.2.4 Compaction Characteristics

Compaction characteristics of sludge are usually evaluated in the laboratory by Standard or Modified Proctor tests in which the variation of dry densities of the sludge compacted at different moisture contents are determined. The compaction energy can be varied to simulate the compaction methods that may be applied in the field. The results can be used to estimate landfilling volume and to provide information for placement control.

Typical compaction characteristics for a number of FGD sulfite sludges are summarized in Table 2-5. It is noted that LSDA sludge can be compacted to higher maximum density as compared with other FGD sludges.

Typical compaction curves of untreated sludge generated by various FGD processes are given in Figure 2-4.

It was pointed out in Fox et al, (1982) that the sludge produced from the same process often has large differences in compaction characteristics due to normal operational variability of the scrubber as shown in Table 2-6. It was recommended that new samples should be used since repeated dynamic compaction can reduce the particle size of the material.

From a practical point of view, in situ density is more important in determining the behaviours of the disposed waste, which is dependent on the method of placement on site. More field density records are required for a thorough understanding of the compaction characteristics of FGD sludge and for the evaluation of an optimum solution for sludge handling and placement.

2.2.5 Shear Strength Characteristics

Shear strength characteristics of the sludge are important parameters in determining the stability of the landfill and the methods of placing the sludge.

Shear strength parameters are dependent on the degree of compaction, density, moisture content, and bonding between particles of the materials.

Klym and Dodd, (1974) reported that as-produced sludges were usually too wet to be handled even though they were dewatered to 65% of solids content.

The Mohr-Coulomb envelopes of a typical dual alkali and a wet scrubbing laboratory compacted filter cake tested under consolidated drained conditions are given in Figure 2-5. The filter cakes have little or no cohesion and have an internal angle of friction of 31.0° to 36.8°, which are typical values for FGD sludge (Krizek, 1979). Krizek et al, (1987) concluded that the drained shear strengths of typical FGD sludge are primarily frictional in nature with a small cohesion component.

The shear strength parameters of typical FGD sludge are summarized in Table 2-7.

Typical for FGD sludges, very few data are available on the in situ shear strength. Krizek, (1979) had measured in situ shear strength in a FGD waste landfill with shear vane test and the results showed that the in situ shear strengths were very low.

2.2.6 Permeability

The permeability characteristics of FGD sludges disposed of within landfilling are important in determining the quantity and migration rate of leachate.

Permeability depends mainly on the pore size distribution of the materials and the physical nature of the pore fluid. The pore size distribution is in turn governed by the compaction characteristics and the particle size distribution of the materials.

The coefficients of permeability reported on typical FGD sludges are within 1×10^{-4} cm/sec to 1×10^{-6} cm/sec (Krizek et al, 1987) and are summarized in Table 2-8.

Permeability of dual alkali sludges were observed to be slightly higher than that of scrubber sludges.

Similar to the behaviour of soils, the permeability of FGD sludge increases with increasing void ratio as shown in Figure 2-6. In addition, permeability decreases with increasing solids content and a rough estimation of the coefficient of permeability can be made from Figure 2-7 if the solids content of the sludge is known. Table 2-9 gives a comparison of permeability of settled and drained sludges and generally shows a permeability decrease with compacted sludges.

2.2.7 Compressibility and Consolidation Characteristics

The self-weight of the sludge during filling will impose consolidation pressure on the underlying materials in the landfill. The compressibility and consolidation characteristics of FGD sludge are therefore important parameters in determining the magnitude and the rate at which the FGD sludge landfill settles with time.

The compressibility and consolidation characteristics of soils are generally evaluated in the laboratory by means of a one dimensional consolidation test. The same test has been used to study the compressibility of FGD sludges.

Typical consolidation curves and the compression indices of a few FGD sulfite sludges are presented in Figure 2-8. The untreated sludges are highly compressible.

Presented in Figure 2-9 is a typical relationship between void ratio and log time obtained from a consolidation test. It can be seen that primary consolidation occurred almost instantaneously and secondary consolidation was significant.

CHAPTER 2

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TABLE 2-1

MINERALOGY OF UNTREATED FGD SLUDGES

TYPE OF FGD PROCESS	SAMPLE SOURCE	MINERALOGY	REFERENCE
Wet Lime Scrubbing	Paddy's Run	94% Sulfite 2% Sulfate 4% Fly Ash	Hagerty et al, 1977
	Kentucky	Sulfite (Platelet Crystals)	Hagerty & Ullrich, 1980
	Ohio	Sulfite (Platelet Crystals)	Hagerty & Ullrich, 1980
	Mohave	95% Sulfate	Hagerty et al, 1977
Wet Limestone Scrubbing	Alabama	Sulfite (Agglomerate Crystal)	Hagerty & Ullrich, 1980
	-	20% Sulfite 50-75% Sulfate 5-30% Limestone	Hagerty et al, 1977
Lime Dual Alkali	ADL/CEA	70% Sulfite 30% Sulfate	Hagerty et al, 1977
	Kentucky	Sulfite (Agglomerate Crystals)	Fox et al, 1982
	FMC	50% Sulfite & Sulfate	FMC, 1987
Limestone Dual Alkali	Scholz Plant	66% Sulfite 33% Sulfate	Fox et al, 1982

(CV12)

TABLE 2-2

SPECIFIC GRAVITY AND LIQUID LIMIT OF UNTREATED FGD SLUDGES

TYPE OF FGD PROCESS	SAMPLE SOURCE	SPECIFIC GRAVITY	LIQUID LIMIT %	REFERENCE
Wet Lime Scrubbing	Paddy's Run	2.49	65	Fox et al, 1982
	Ohio	2.46	59	Fox et al, 1982
	Kentucky	2.49	31	Fox et al, 1982
Wet Limestone Scrubbing	Mid-West Limestone	2.68	-	Hagerty et al, 1977
	Alabama	2.52	24	Fox et al, 1982
	Ontario Hydro	2.86	-	Klym & Dodd, 1974
Lime Dual Alkali	ADL-CEA	2.56	-	Fox et al, 1982
	Pennsylvania	2.72	45	Krizek, 1979
	Kentucky	2.56-2.70	38-43	Fox et al, 1982
Limestone	Scholz	2.55	34	Fox et al, 1982

(CV12)

TABLE 2-3

WATER CONTENT OF UNTREATED FGD SLUDGES

TYPE OF FGD PROCESS	SAMPLE SOURCE	WATER CONTENT % SETTLED	DRAINED	CENTRIFUGE	FILTER	REFERENCE
Wet Lime Scrubbing	Shawnee Lime	141	130	100	78.5	Rossoff et al, 1979
	Duquesne Lime	110	88	75	75	Rossoff et al, 1979
Wet Limestone Scrubbing	Shawnee Limestone	89-104	72-80	58-67	52-54	Rossoff et al, 1979
	Choka Limestone	114	97	64	87	Rossoff et al, 1979
	Mohave Limestone	50	49	30	25	Rossoff et al, 1979
Lime Dual Alkali	GM	150	128	97	73	Rossoff et al, 1979
	Utah	169	142	61	83	Rossoff et al, 1979
Limestone Dual Alkali	Scholz	-	-	-	107-139	Fox et al, 1982
	Schahfer (Huber Q295)	-	-	-	27-52	Lee et al, 1987
	Schahfer (Marblehead)	-	-	-	56-64	Lee et al, 1987

(CV13)

TABLE 2-4

SOLIDS CONTENT OF UNTREATED FGD SLUDGES

TYPE OF FGD PROCESS	SAMPLE SOURCE	SOLIDS CONTENT % SETTLED	SETTLED/ DRAINED	CENTRIFUGE	FILTERED	REFERENCE
Wet Lime Scrubbing	Shawnee Lime	41.5	43.4	49.9	56.0	Rossoff et al, 1979
	Duquesne Lime	47.6	53.1	57.2	57.0	Rossoff et al, 1979
Wet Limestone Scrubbing	Shawnee Limestone	49-52.9	55.7-58.3	59.8- 63.3	65.0-65.9	Rossoff et al, 1979
	Choka Limestone	46.7	50.3	60.9	53.4	Rossoff et al, 1979
	Mohave Limestone	66.6	67.2	77.0	80.3	Rossoff et al, 1979
Lime Dual Alkali	GM	40.0	43.9	50.9	57.8	Rossoff et al, 1979
	Utah	37.2	41.4	62.2	54.6	Rossoff et al, 1979
	Pennsyl-vania	-	-	-	60	Krizek, 1979
Limestone Dual Alkali	Scholz	-	-	-	41.9-48.4	Fox et al, 1982
	Schahfer (Huber Q295)	-	-	-	66-79	Lee et al, 1987
	Schahfer (Marblehead)	-	-	-	61.64	Lee et al, 1987

(CV13)

TABLE 2-5

COMPACTION CHARACTERISTICS OF UNTREATED FGD SLUDGES

TYPE OF FGD PROCESS	SAMPLE SOURCE	ρd MAX Kg/m^3	W opt %	REFERENCE
Wet Lime Scrubbing	Paddy's Run	1350	31	Hagerty et al, 1977
	Ohio	1280	37	Hagerty & Ullrich, 1980
	Kentucky	1400	30	Hagerty & Ullrich, 1980
	Northwestern	1350	33	Krizek et al, 1987
Wet Limestone Scrubbing	Ontario Hydro	1364	35	Klym & Dodd, 1974
	Alabama	1730	15	Hagerty & Ullrich, 1980
	Northwestern	1650	18	Krizek et al, 1987
Lime Dual Alkali	Kentucky	1410 - 1480	23 - 28	Hagerty & Ullrich, 1980
	ADL/CEA	1360	27	Hagerty et al, 1977
	Northwestern	1170 - 1360	27 - 34	Krizek et al, 1987
	Pennsylvania	1120	42	Krizek, 1979
Limestone Dual Alkali	Scholz (Standard Proctor)	1680	15	Fox et al, 1982
	Scholz (100 psi Static Compaction)	1550	17	Fox et al 1982

(CV12)

TABLE 2-6

COMPACTION CHARACTERISTICS
OF LSDA SLUDGE OBTAINED FROM DIFFERENT PERIODS

(Fox et al, 1982)

SAMPLE DATE	SAMPLE	ρd MAX Kg/m^3	Wopt %	SOLIDS CONTENT AT Wopt (%)
7-75	New Sample	1140	33.3	75.0
10-75	Reuse Sample	1360	26.4	79.1
6-76	New Sample	920	55.0	64.5
6-76	Reuse Sample	1220	38.0	72.5

(CV12)

TABLE 2-7

SHEAR STRENGTH PARAMETERS OF UNTREATED FGD SLUDGES

TYPE OF FGD PROCESS	SAMPLE SOURCE	SHEAR STRENGTH PARAMETERS C' KN/m^2	Ø' Deg	QU KN/m^2	REFERENCE
Wet Lime Scrubbing	Paddy's Run	34.5	31	-	Hagerty & Ullrich, 1980
Wet Limestone Scrubbing	-	-	-	90-240	Rossoff et al, 1979
Lime Dual Alkali	Pennsylvania*	0	35-40	300	Krizek, 1979
	ADL/CEA	0	36.4	-	Hagerty & Ullrich, 1980
Limestone Dual Alkali	Schahfer (Huber Q295)	-	-	54-103	Lee et al, 1987
	Schahfer (Marblehead)	-	-	46-54	Lee et al, 1987

(CV12)

* Drained direct shear test.

TABLE 2-8

PERMEABILITY OF UNTREATED FGD SLUDGES

TYPE OF FGD PROCESS	SAMPLE SOURCE	CONSOLIDATION PRESSURE KN/m^2	COEFFICIENT OF PERMEABILITY cm/sec.	REFERENCE
Wet Lime Scrubbing	Shawnee Lime	207	1.1×10^{-5} - 1.4×10^{-5}	Rossoff et al, 1979
		6900	7.3×10^{-6}	
	Duquesue	-	1.5×10^{-4}	Hagerty et al, 1977
	Phillips	-	6×10^{-5}	Hagerty et al, 1977
Wet Limestone Scrubbing	Shawnee Limestone	-	6×10^{-5} - 2.5×10^{-4}	Hagerty et al, 1977
	Mohave	-	1.5×10^{-4} - 6×10^{-4}	Hagerty et al, 1977
Lime Dual Alkali	Scholz	207	4.4×10^{-4}	Rossoff et al,
		6900	1.4×10^{-4}	1979
	Pennsyl-vania	-	10^{-5} - 10^{-6}	Krizek, 1979
Limestone Dual Alkali	Schahfer (Huber Q295)	-	1.9×10^{-4} - 7.2×10^{-4}	Lee et al, 1987
	Schahfer Marblehead	-	7×10^{-5} - 1.5×10^{-4}	Lee et al, 1987

(CV12)

TABLE 2-9

PERMEABILITIES OF UNSTABILIZED FGD SLUDGES

(Coltharp et al, 1979)

LOCATION	PROCESS	SETTLED OR DRAINED		COMPACTED	
		Void Ratio	Coef. of Perm. (cm/sec)	Void Ratio	Coef of Perm. (cm/sec)
Eastern	Limestone				
	Sample 1	1.53	1×10^{-4}	1.24	8×10^{-5}
	Sample 2	2.07	3×10^{-5}	1.56	1×10^{-5}
Eastern	Lime				
	Sample 1	1.83	2×10^{-4}	1.68	5×10^{-5}
	Sample 2	1.65	6×10^{-5}	1.42	1×10^{-5}
	Sample 3	1.25	1×10^{-4}	0.97	7×10^{-5}
Western	Limestone				
	Sample 1	0.96	3×10^{-5}	0.63	1×10^{-5}
	Sample 2	1.20	2×10^{-5}	1.20	1×10^{-5}
	Sample 3	0.75	8×10^{-4}	0.50	9×10^{-5}
Eastern	Dual Alkali				
	Sample 1	5.11	8×10^{-5}	4.17	3×10^{-5}
	Sample 2	2.19	2×10^{-4}	1.95	8×10^{-5}
Western	Dual Alkali	2.77	1×10^{-3}	2.61	1×10^{-4}

(CV12)

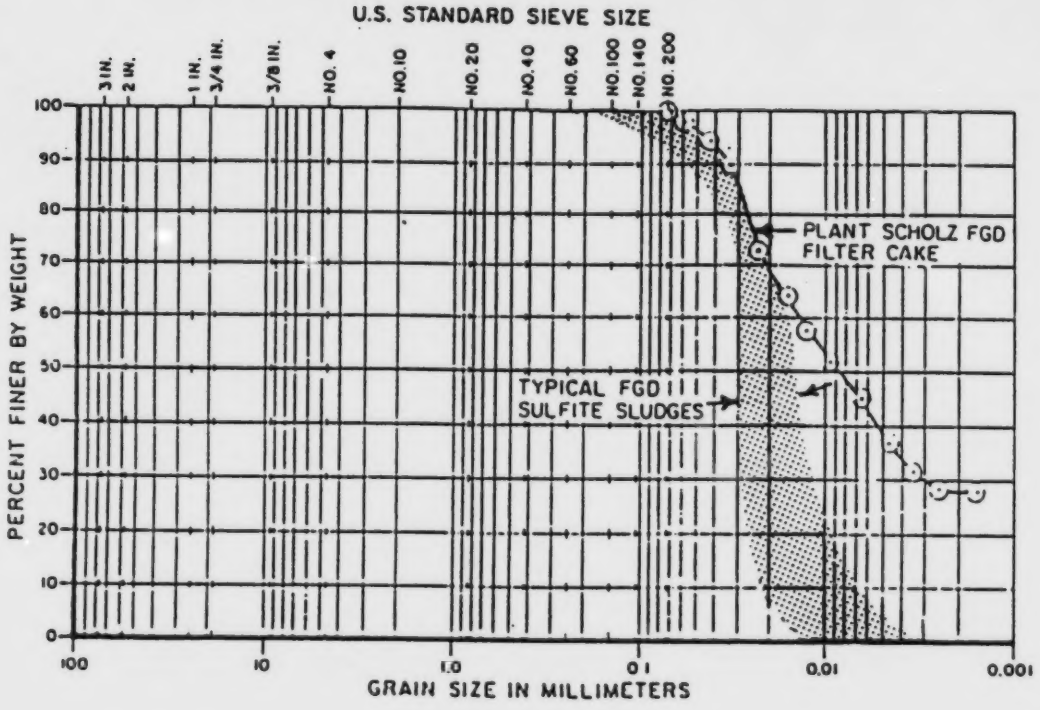


FIGURE 2-1

PARTICLE SIZE DISTRIBUTION OF UNTREATED FGD FILTER CAKE (LSDA PROCESS) (FOX ET AL, 1982)

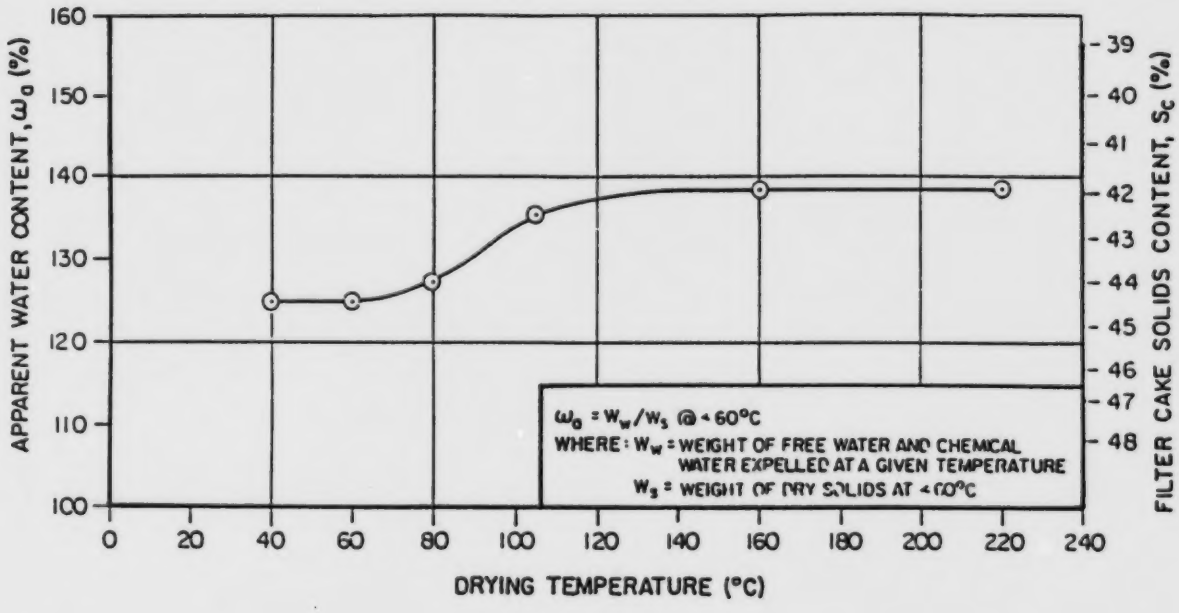


FIGURE 2-2

APPARENT WATER CONTENT VERSUS DRYING TEMPERATURE FOR A LSDA FILTER CAKE FROM PLANT SCHOLZ (FOX ET AL, 1982)

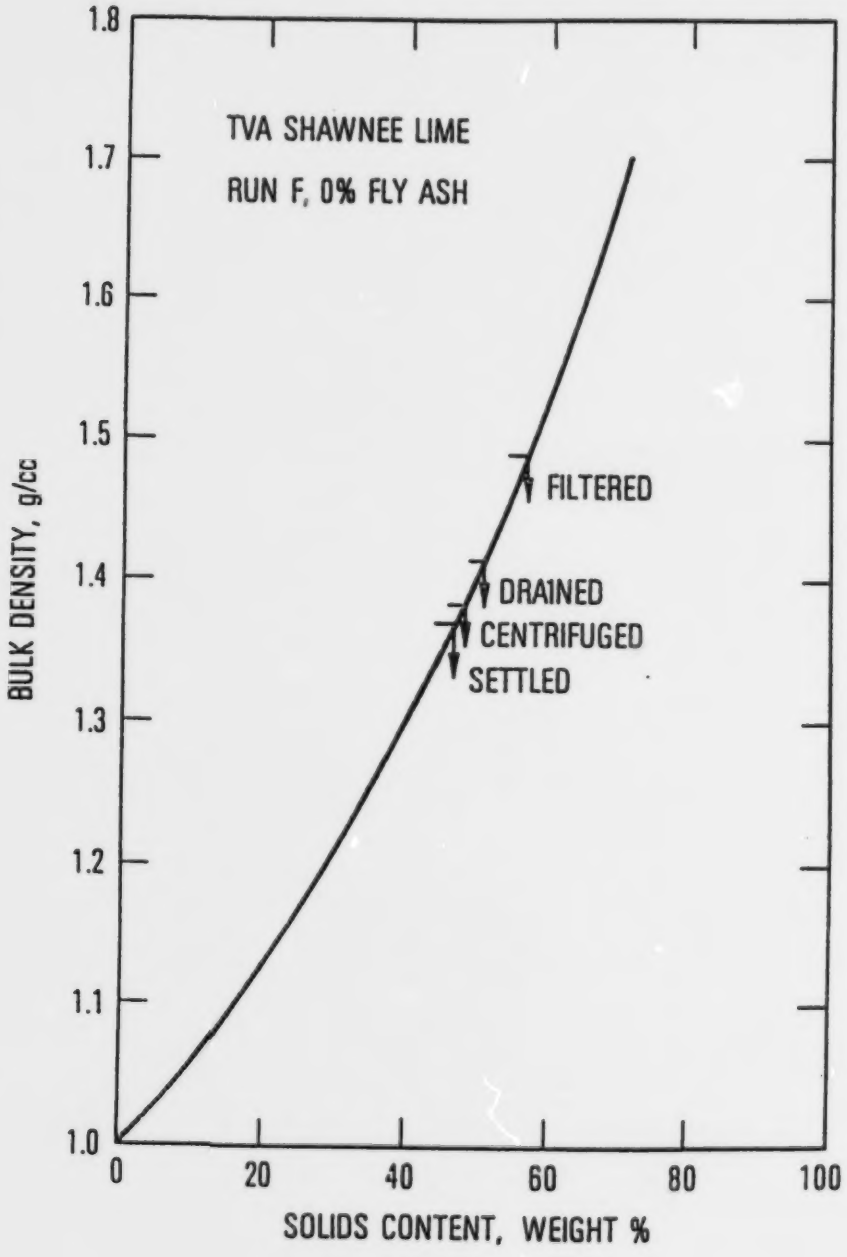


FIGURE 2-3

BULK DENSITY AS A FUNCTION OF SOLIDS CONTENT: TVA SHAWNEE LWS SLUDGE WITHOUT STABILIZATION (ROSSOFF ET AL, 1979)

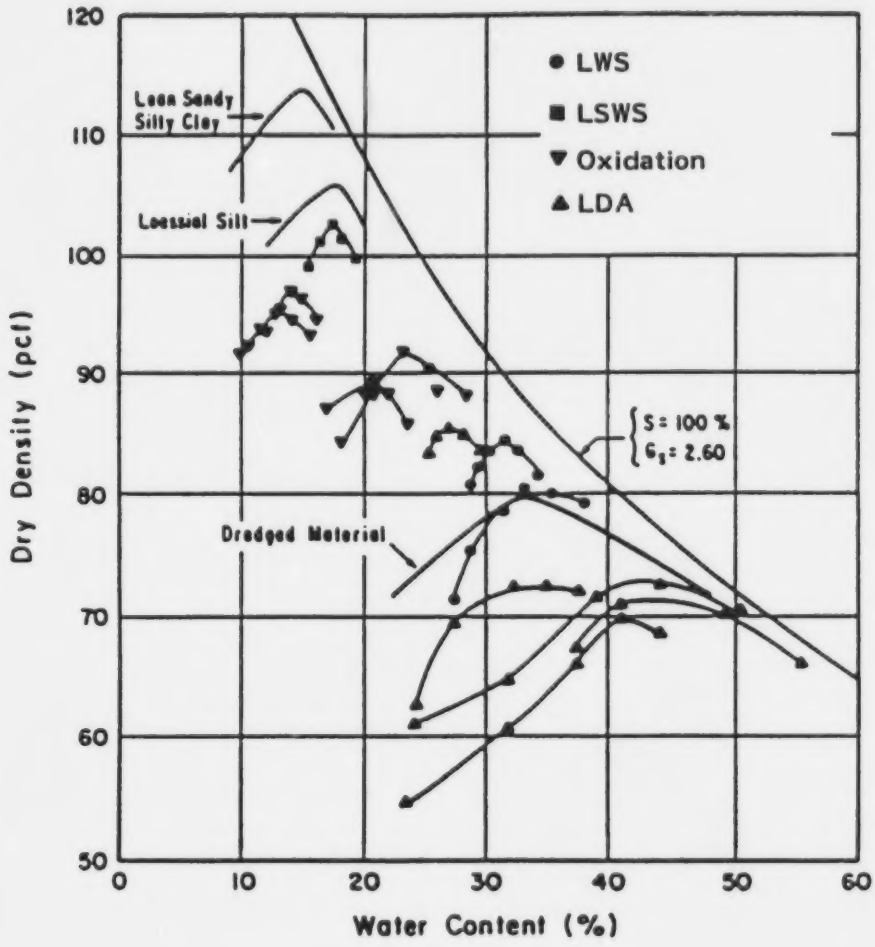
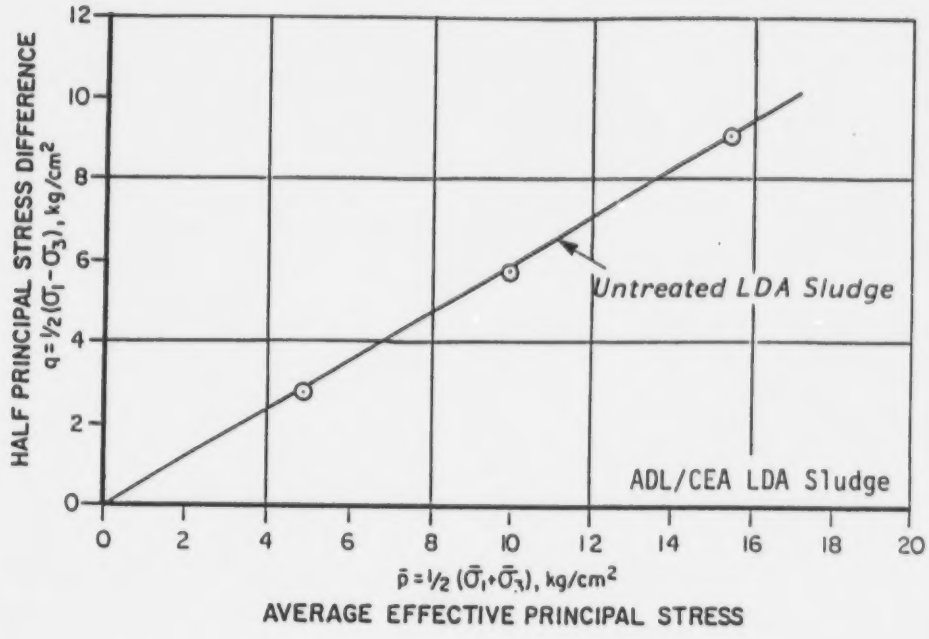


FIGURE 2-4
COMPACTION CURVES FOR UNTREATED FGD SLUDGES
(KRIZEK ET AL, 1987)



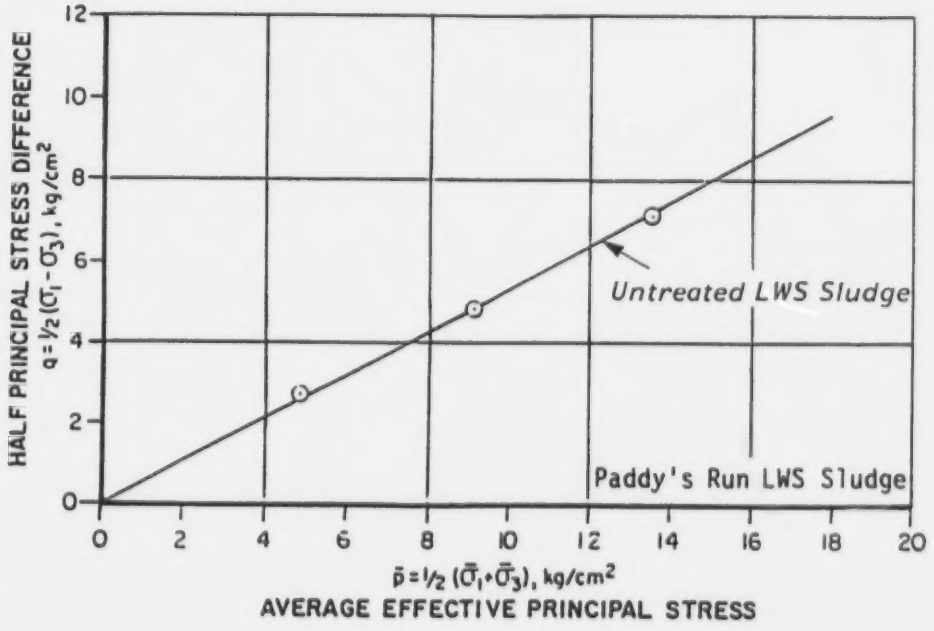


FIGURE 2-5
TYPICAL MOHR-COULOMB PARAMETERS FOR
FGD SULFITE SLUDGES
(HAGERTY AND ULLRICH, 1980)

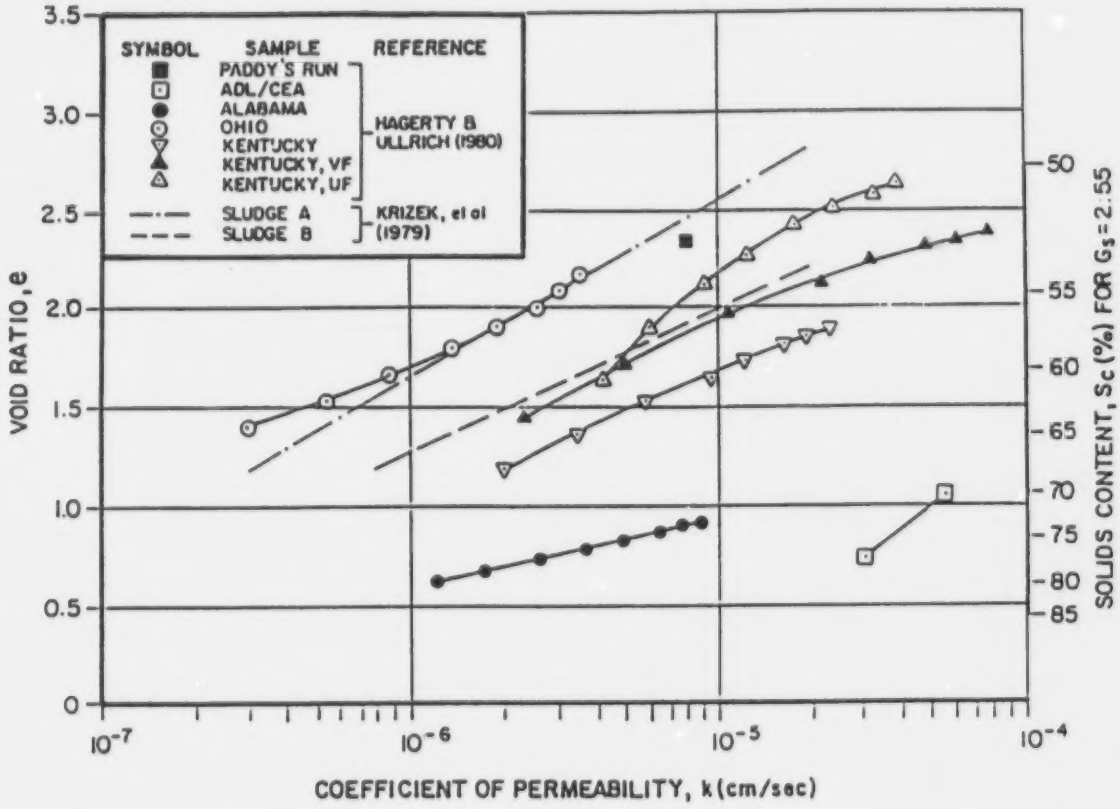


FIGURE 2-6

VOID RATIO VERSUS COEFFICIENT OF PERMEABILITY
FOR SULFITE FGD SLUDGES
(HAGERTY & ULLRICH 1980 & KRIZEK ET AL, 1979)

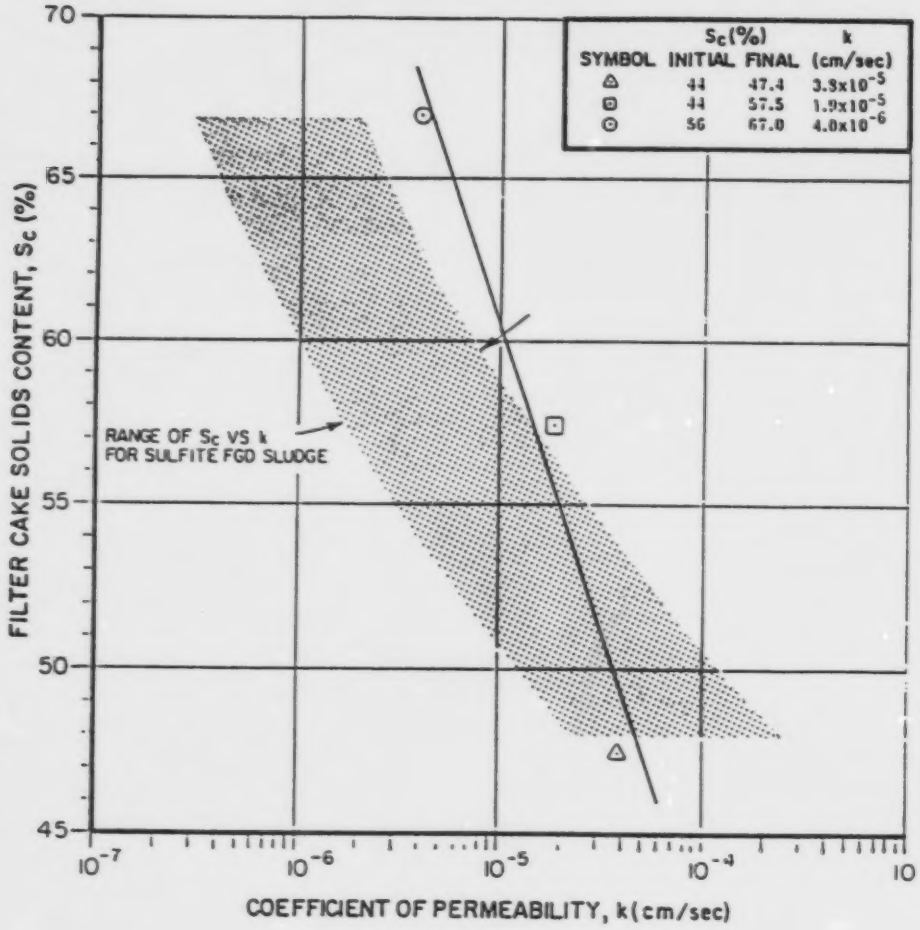
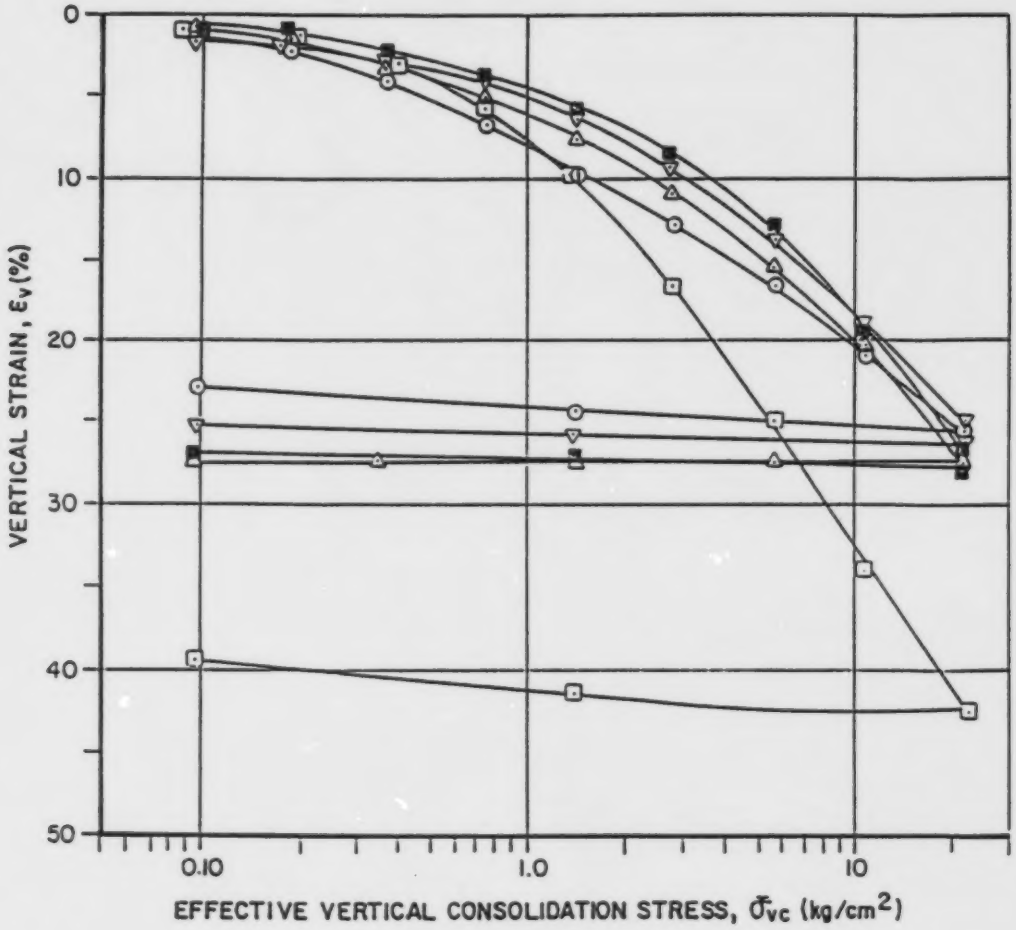


FIGURE 2-7

SOLIDS CONTENT VERSUS COEFFICIENT OF PERMEABILITY OF TREATED AND UNTREATED FGD FILTER CAKE (FOX ET AL, 1982)



SYMBOL	SAMPLE	ω_n (%)	e_o	CR ($\bar{\sigma}_{vc}$>3 kg/cm^2)
⊡	PADDY'S RUN	200	3.22	0.29
■	ADL/CEA	86	2.00	0.24
⊙	OHIO	131	2.25	0.15
▽	KENTUCKY	100	1.96	0.19
△	KENTUCKY, UF	138	2.70	0.21

SOURCE: Hagerty, D.J. & Ullrich, C.R. (1980). "Interim Report-Physical Characterization of FGC Wastes". Report to Arthur D. Little, Inc., EPA Contract 68-02-2654.

FIGURE 2-8
COMPRESSIBILITY CHARACTERISTICS OF UNTREATED FGD SULFITE SLUDGES (FOX ET AL, 1982)

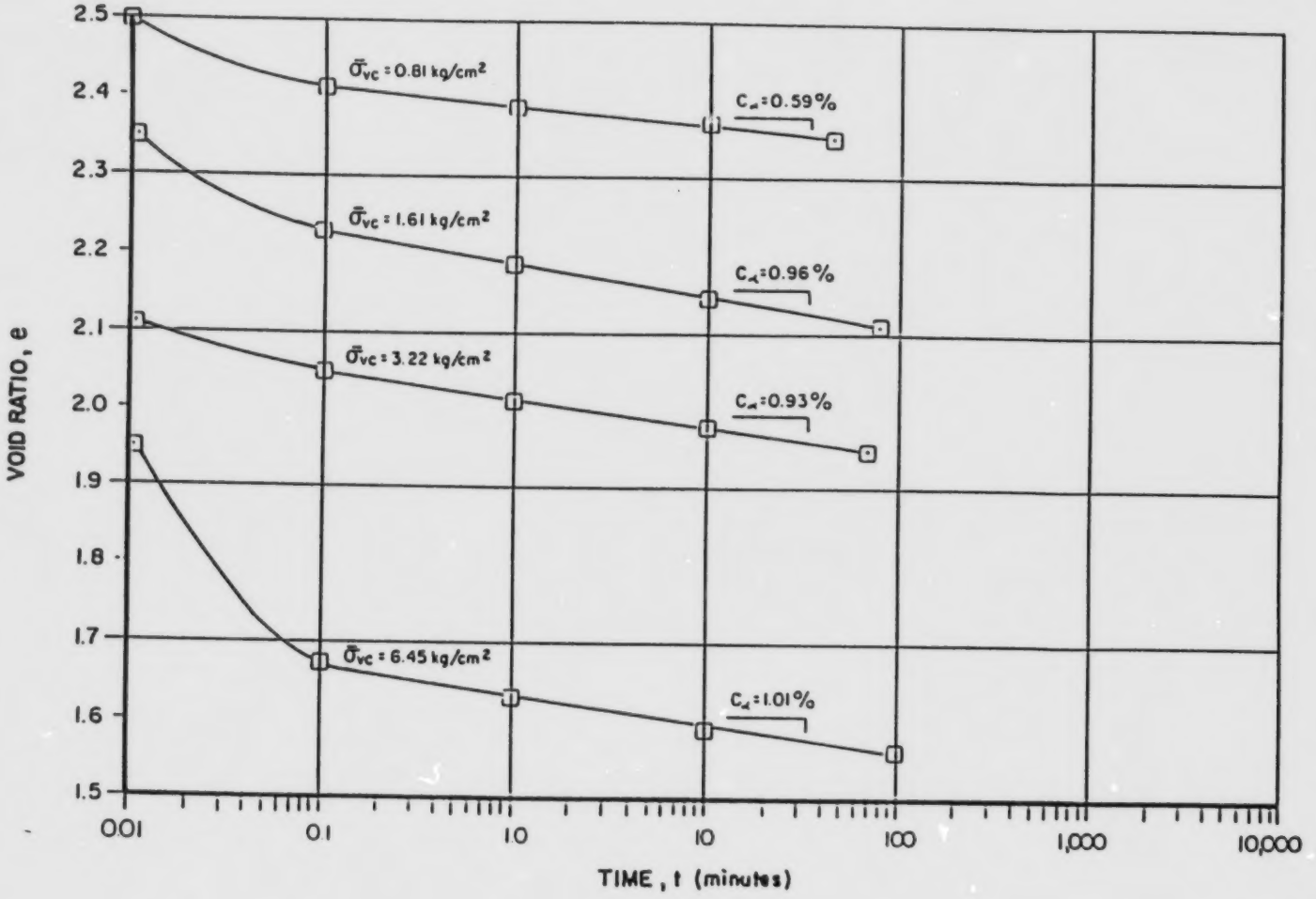


FIGURE 2-9
TYPICAL VOID RATIO VERSUS TIME CONSOLIDATION CURVES FOR
A LSDA FILTER CAKE FROM PLANT SCHOLZ
(FOX ET AL, 1982)

3.0 ENGINEERING CHARACTERISTICS OF STABILIZED LSDA SLUDGE/FILTER CAKE

Background

A number of researches have been documented on the characteristics of the wastes produced by various FGD processes such as Lime/Limestone scrubbing and Lime Dual Alkali (Hagerty et al, 1977, Krizek, 1979, Rossoff et al, 1979, Krizek et al, 1987, etc.). However, desulfurization by means of dual alkali process using limestone as the absorbent (LSDA) is a relatively new concept. Owing to the anticipated low cost and high efficiency of this process, two pilot test programs were implemented by the U.S. Electric Power Research Institute (EPRI). The results of the studies were presented in Fox et al, (1982) and Lee et al, (1987).

The first comprehensive LSDA landfill disposal test program was described in Fox et al, (1982). Sponsored by the U.S. Environmental Protection Agency, a prototype limestone dual alkali fuel gas desulfurization system was tested for an eight-month period at Scholz Electric Generating Station at Gulf Power Company in Sneads, Florida. The wastes produced were disposed of in a trial landfill site. The potential problems relating to the waste handling and landfilling were analysed and studied. The purpose of the evaluation was to determine the engineering characteristics of the LSDA sludge, the potential landfill disposal construction and management problems, and the characteristics of leachate and run-off from the landfill. An extensive laboratory testing program was implemented to characterize the waste and to evaluate various methods in stabilizing the sludge for landfilling. A field monitoring program was also carried out to verify the laboratory results. It was concluded that the sludge produced from the LSDA process can be stabilized and disposed of by landfilling with no potential hazard to the environment. In addition, revegetating the landfill site was also studied.

Another pilot plant testing on the LSDA FGD process was described in Lee et al, (1987). A 3 MW LSDA operating on a slipstream of a commercial 420 MW boiler burning 3.5 percent, high sulfur coal at Schahfer station was tested for 65 days. The objectives of the studies were to evaluate the efficiency of the LSDA process and the characteristics of the wastes produced regarding handling, disposal and environmental impacts.

It is attempted in this chapter to summarize all the available information on the characteristics of the waste produced by the LSDA process as a data base for the design and evaluation for an optimum disposal scheme.

3.1 Physical and Chemical Properties of Laboratory Stabilized LSDA Sludge/Filter Cake

3.1.1 General

Owing to the high water content, low shear strength, and high compressibility, the LSDA sludge must be stabilized for easy handling and disposal. The use of mixing fly ash and lime with the LSDA filter cake was evaluated and reported in Fox et al, (1982) and the results are summarized below.

The LSDA filter cake produced by the Scholz LSDA plant had a solids content in the range of 45-55%. The amount of fly ash/filter cake ratios and lime content were varied in specified proportion for parametric studies. The fly ash to filter cake ratios used were 0.75 and 1.00 and the lime contents were 1.0, 3.0 and 5.0%. The curing time of the stabilized samples were varied at 3, 7, 14, 28, and 58 days. Air curing, humid curing and constant-moisture curing were employed in order to evaluate the effect of curing time and curing environment on the properties of the stabilized sludge. Air curing was used to simulate curing at the surface of the landfill, humid curing for saturated sludge and constant-moisture curing for the sludge at greater depth.

3.1.2 Properties of the Additives: Fly Ash and Lime

3.1.2.1 Fly Ash

The fly ash used in stabilizing the filter cake was collected from electrostatic precipitation and its index properties are summarized in Table 3-1.

The particles of the fly ash are spherical and the size ranges from less than 1 μm to 35 μm, with aggregates of particle as large as 100 μm in diameter. The overall chemical composition in the order of abundance was reported to be Al, Si, Fe, K, Ca and traces of Ti and V.

The fly ash was a uniform silt-size material with 95% of the particles finer than 74 μm and approximately 4% finer than 2 μm. The specific gravity of the fly ash was 2.55. It had a pH of 2.5 to 3.5 and a specific conductance of 6,200 to 7,600 umhos/cm. The natural moisture content and solids content varied from 0.11 to 0.2% and 99.89 to 99.80%, respectively. When dried at 105°C for 24 hours, the fly ash had an average natural moisture and solids content of 0.14% and 99.86%, respectively.

3.1.2.2 Lime

A commercial lime was used which had a natural moisture content of 0%, solids content of 100% and a specific gravity of 2.27. The pH and specific conductance of the lime in distilled water at a dilution of 2.0 were 13.0 and 7,800 umhos/cm,, respectively. The properties of the lime are presented on Table 3-1.

3.1.3 Physical and Chemical Properties of the Stabilized LSDA Sludge

Several laboratory mixes of filter cake, fly ash and lime were prepared for index, compaction, strength, permeability, consolidation and leaching studies to characterize the relative effects of filter cake solids content, fly ash to filter cake ratio and lime content on engineering behaviours. The filter cake had a solids content in the range of 45-55%. For stabilization and fixation to be effective, fly ash to filter cake ratios of 0.75 to 1.00 and the lime contents of 1.0 to 5.0% were used.

3.1.3.1 Index Properties of the Stabilized LSDA Sludge

Particle Distribution

Particle size distributions obtained from sieve and hydrometer analyses on mixtures with filter cake solids contents of 47 and 56%, fly ash to filter cake ratios of 0.75 and 1.00, and lime content of 3% are shown in Figures 3-1 and 3-2. The results are consistent with the particle size distributions measured on the pond mix and separately on filter cake and fly ash indicating 99 to 100% of the particles finer than the 74 μm size and 20 to 27% finer than the 2 μm size as shown in Table 3-1.

Specific Gravity

The specific gravity of the stabilized sludge is given in Table 3-2 which indicates values of 2.61 to 2.68 with an average of 2.65. These specific gravities agree with the 2.60 and 2.69 values measured on pond mix stabilized sludge. The consistent average of 2.65 measured on laboratory and pond mix sludge sample is higher than the specific gravities of 2.55 and 2.27 measured on the individual components of the mixes (Table 3-1).

Water Content

The natural water content of the mixture varied from 38.1 to 62.6% with corresponding solids content of 72.4 to 61.5% and covers the range of natural moisture contents likely to occur. As indicated in Figure 3-3, the natural water content decreased with an increasing amount of fly ash and decreased slightly with the increase of lime content.

Liquid Limit

Liquid limits of the mixtures vary from 39.3 to 54.0% as shown in Table 3-2. In general, the natural water contents are higher than the corresponding liquid limits for the filter cake with 47% of solids content and are slightly lower for the filter cake with 56% of solids content as shown in Figure 3-3.

pH and Specific Conductance

The pH and specific conductance of the laboratory mixes ranged from 7.9 to 12.7 and 16,000 to 31,000 umhos/cm, respectively as shown in Table 3-2. Samples with 1% lime yielded lower pH values of 7.9 to 9.2, whereas samples with 3.0 to 5.0% lime yielded similar pH values of 12.1 to 12.7. There is a slight indication of decreasing specific conductance with increasing solids content.

3.1.3.2 Compaction Characteristics

The compaction characteristics of Plant Scholz filter cake, fly ash and stabilized sludge mixture were determined with static compaction tests. Standard proctor tests were also performed on filter cake and fly ash

separately for comparison to the static tests. Stabilized sludge with fly ash to filter cake ratios of 0.75, 1.0 and 1.3 all with a uniform lime content of 3.0% were tested and the results are summarized in Figure 3-4.

The maximum dry density of the stabilized sludge mixtures increased with decreasing fly ash content and the optimum moisture content decreased with decreasing fly ash content. For the range of fly ash to filter cake ratios of 0.75 to 1.00, which are of the most practical interest, the maximum dry density and optimum water content vary from 1470 kg/m3 at 26.5% to 1284 kg/m3 at 36.5%, respectively. A comparison of dry densities of the stabilized sludge at natural water content and optimum water content is presented in Table 3-3.

The engineering properties of stabilized FGD sludge mixtures are of most interest for conditions that will exist after placement within landfills. Therefore, while the engineering properties of stabilized sludges at the optimum moisture content are of interest from a research perspective, the engineering properties of sludges at the natural moisture content as existing in the landfill are of considerable more practical importance.

3.1.3.3 Shear Strength Characteristics

3.1.3.3.1 Isotropically Consolidated Drained Triaxial Tests

General

A number of triaxial and unconfined compression tests were performed on the mixed stabilized sludge.

The triaxial testing program on laboratory prepared mixes consisted of strain controlled isotropically consolidated drained triaxial compression tests (CIDC). A series of strain controlled isotropically consolidated undrained triaxial compression tests with pore pressure measurements (CIUC) were also performed on remoulded pond mix samples.

Six laboratory prepared samples were selected for triaxial compression testing. The samples were selected to provide a range of filter cake solids content, fly ash to filter cake ratios and lime contents. All samples were constant-moisture cured for 28 days prior to testing. Typical results are shown in Figure 3-5.

Effect of Lime Content

The effect of the quantity of lime to be added for fixation was investigated for samples prepared with a filter cake solids content of 56%, fly ash to filter cake ratio of 0.75 and lime contents of 1.0, 3.0 and 5.0%. The Mohr-Coulomb parameters obtained from each test are summarized in Table 3-4 and also in Figures 3-6. A few important observations are summarized below:

The results from the triaxial tests clearly indicate that effective cohesion (c') increased with increasing lime content as shown in Figure 3-6.

For samples with 1.0% lime, the cohesion was relatively small. As the amount of lime increased, the cohesion component increased significantly as shown in the figure.

The greatest increase in effective cohesion occurred between 3.0 and 5.0% lime content.

At lower stress levels where cohesion was the dominant component of strength, the mixture with 3.0% lime yielded a higher shear strength. The range of stresses likely to occur within or will be imposed upon a reclaimed stabilized FGD sludge landfill, would be within the lower stress levels where the cohesion component of strength dominates and the 3.0% lime mixture yields the higher shear strength.

The friction angle ($\emptyset'$) decreased with increasing lime content (Figure 3-6).

For samples with 1.0% lime, the angle of friction was relatively large.

As the amount of lime increased, the angle of friction decreased slightly as shown in Figure 3-6.

The greatest decrease in the angle of friction occurred between 1.0 and 3.0% lime content, from 39.9° to 36.8°, but appeared to remain constant above a lime content of 3.0%. It was anticipated that further additions of lime would not be expected to significantly decrease the effective friction angle.

As shown in Figure 3-6, the overall increase in shear strength due to lime addition between mixes with 1.0 and 3.0% lime is relatively small in comparison to the increase occurring with 5.0% lime.

Effect of Fly Ash to Filter Cake Ratio

The effect of the fly ash to filter cake ratio on the shear strength of stabilized sludge was investigated for samples prepared with a 3.0% lime content, filter cake solids content of 47 and 56% and fly ash to filter cake ratios of 0.75 and 1.00.

The Mohr-Coulomb parameters obtained from each test are presented in Table 3-4.

In general, the results indicate that both effective cohesion and the angle of internal friction increased with fly ash to filter ratios. The details of the effect are analyzed below.

The effective cohesion (c') increased with increasing fly ash.

For samples with solids content of 47%, the effective cohesion increased approximately 20% as the fly ash to filter cake ratios increased from 0.75 to 1.00.

For samples with solids content of 56%, the effective cohesion increased approximately 7% as the fly ash to filter cake ratios increased from 0.75 to 1.00.

The effective angle of internal friction ($\emptyset'$) increased with increasing fly ash to filter cake ratios.

For samples with solids content of 47%, the effective angle of internal friction increased from 37.5° to 39.0° as the fly ash to filter cake increased from 0.75 to 1.00.

For samples with solids content of 56%, the effective angle of internal friction increased from 36.8° to 39.3° as the fly ash to filter cake increased from 0.75 to 1.00.

It was also reported that the stress-strain behaviour of the samples consistently indicated a lower vertical strain at failure, less positive volume change (contraction) during drained shear and a higher Young's modulus at failure as the fly ash to filter cake ratio increased from 0.75 to 1.00.

Effect of Filter Cake Solids Contents

The effect of the filter cake solids content on shear strength was determined using the same series of samples as for studying the effect of fly ash and lime content as described above. The samples tested have solids content of 47 and 56% respectively. Important observations are summarized below.

Effective cohesion (c') increased with increasing solids content as shown in Figure (3-7)).

For samples with fly ash to filter cake ratios of 0.75, c' increased 34% as solids content increased from 47 to 56%.

For samples with fly ash to filter cake ratios of 1.00, c' increased 21% as solids content increased from 47 to 56%.

Effective angle of internal friction ($\emptyset'$) was only slightly affected by the amount of solids content (Figure 3-7).

For samples with fly ash to filter cake ratios of 0.75, $\emptyset'$ decreased by 0.7 as solids content increased from 47 to 56%.

For samples with fly ash to filter cake ratios of 1.00, $\emptyset'$ increased by 0.3° as solids content increased from 47 to 56%.

3.1.3.3.2 Unconfined Compression Tests

Eight laboratory prepared mixes of cured stabilized FGD sludge were selected for unconfined compression testing. Samples were cured using air curing, humid curing and constant-moisture curing to determine the effect of curing environment on shear strength characteristics. Curing time of 3, 7, 14, 28

and 56 days were used to investigate the effect of curing time on shear strength characteristics and the time required to obtain a given percentage of the ultimate strength.

The results of the unconfined compression test programs are summarized in Figures 3-8 and 3-9.

Effect of Curing Environment

The effect of curing environment on the unconfined compressive strength, (Qu), was investigated for air curing, humid curing and constant-moisture curing conditions. Air curing simulates the conditions where the FGD sludge is exposed as those at the surface of landfilling. Humid curing is similar to curing conditions that exist within a saturated landfill or stockpile. Constant-moisture curing is similar to curing conditions of the sludge at great depths or within the center of stockpiles. Summarized below are the results of the tests for a different curing environment.

The air cured samples consistently yielded the highest unconfined compressive strength as shown in Figure 3-8. After 28 days, the specimens were practically dry with moisture contents of 0.10 to 0.30%. Some specimens exhibited shrinkage cracks, particularly those with a lime content of 5.0%.

In general, the unconfined compressive strengths of humid cured samples were greater than those obtained with constant-moisture curing. For a lime content of 5.0%, the results were inconsistent. Shrinkage cracks were often developed on the tested specimens.

Constant-moisture curing did not, in general, produce significant shrinkage crack. After 28 days, samples cured under constant-moisture conditions exhibited unconfined compressive strengths of approximately 10, 30, and 65% of the corresponding air-cured values at lime contents of 1.0, 3.0 and 5.0%, respectively, as shown in Figure 3-8.

Effect of Curing Time

The effect of curing time on shear strength characteristics are also indicated in Figures 3-8. The effects are studied in parallel with the curing environments as summarized below.

Air-cured specimens consistently exhibited the most rapid increase in strength with time.

In general, the higher the lime content of the samples, the longer the time required to develop the maximum strength as shown in Figure 3-9.

> Specimens with 1.0 and 3.0% lime displayed the greatest increase in strength within the first 7 days of curing and showed little additional gain thereafter.

With 5.0% lime content, the specimens displayed the greatest increase in strength during the first 14 days of curing and show little additional gain thereafter.

The results of the unconfined compression test on samples cured by means of humid curing were erratic.

For samples cured under constant-moisture condition, maximum shear strengths were developed with longer curing time with increasing lime content as shown in Figure 3-9.

Specimens with 1.0% lime content experienced the greatest strength increase in the first 7 days of curing with little additional strength gain after 7 days.

Specimens with 3.0% lime content displayed the greatest increase in strength during the first 14 days of curing and showed a gradual gain in strength thereafter.

Specimens with 5.0% lime content exhibited the greatest strength increase during the 14 to 28 days curing period and showed a considerable increase in strength during the 28 to 56 days period.

Effect of Lime Content

The effect of the amount of lime added to a stabilized sludge mixture on unconfined compressive strength was investigated for specimens prepared with filter cake solids contents of 47 and 56%, fly ash to filter cake ratios of 1.00 and 0.75 and lime content of 1.0, 3.0 and 3.0%. The unconfined compressive strengths versus curing time for each lime content and curing methods are summarized in Figure 3-8. The results of the tests are summarized below.

Unconfined compressive strength increased with lime content.

The air-cured specimens showed the greatest increase in strength with lime content.

Specimens cured under the constant-curing condition exhibited little increase in strength with 1.0% lime content and showed a greater increase with 3.0 and 5.0% lime content.

Effect of Fly Ash to Filter Cake

The effect of fly ash to filter cake ratio on unconfined compressive strength of stabilized sludge was investigated for samples prepared with a 3.0% lime content, filter cake solids contents of 47% and 56% and fly ash to filter cake ratios of 0.75 and 1.00.

In general, the unconfined compressive strength increased with increasing fly ash to filter cake ratios.

Effect of Filter Cake Solids Contents

Experimental results showed that the unconfined compressive strength increased with increasing filter cake solids content (Fox et al, 1982).

3.1.3.4 Permeability

The effect of filter cake solids content, fly ash to filter cake ratios, lime content and curing time on the permeability of stabilized FGD sludge mixes were studied in the laboratory with constant head permeability tests. Similar to the triaxial tests, the specimens were prepared by compacting the mixed filter cake statically into steel moulds with compaction efforts of 98 and 706 kN/m2 respectively. The samples were cured by means of constant-moisture curing. The results of the tests are summarized in Table 3-5.

3.1.3.4.1 Effect of Curing Time

Presented in Figure 3-10 is the effect of curing time on the coefficient of permeability of stabilized FGD sludge for curing times of 0 to 28 days.

In general, permeability decreased with longer curing time. For lime contents of 1.0 to 3.0%, the reduction was relatively small (about 200 to 300%). For lime contents of 3.0 to 5.0%, however, the permeability decreased approximately 100-fold after curing as shown in Figure 3-10.

3.1.3.4.2 Effect of Lime Content

The effect of lime content on the coefficient of permeability is shown in Table 3-5. For a given solids content, the coefficient of permeability decreased with increasing lime content.

The coefficient of permeability was observed to decrease by a factor of 3 to 12 and 8 to 18 for lime contents increasing from 1.0 to 3.0% and 3.0 to 5.0%, respectively.

Increasing the lime content from 1.0 to 5.0% decreased the coefficient of permeability by a factor of 50 to 90.

It was anticipated that the coefficient of permeability of air-cured samples would be higher because of the formation of shrinkage cracks.

For lime fixation to be significant in reducing permeability, lime contents of 3.0 to 5.0% or greater were recommended in (Fox et al, 1982).

3.1.3.4.3 Effect of Solids Content

The coefficient of permeability was observed to decrease by factors of approximately 4.5, 3 and 6 for a 5% increase in solids content for lime contents of 1.0, 3.0, 5.0%, respectively.

A summary of solids content versus coefficient of permeability for all mixes tested is presented in Table 3-5. In general, the coefficient of permeability increases with increasing solids contents.

3.1.3.4.4 Effect of Compaction

The samples prepared for studying the effect of compaction were compacted at two different compaction efforts. Samples with moisture contents below and near the optimum moisture contents were prepared with 7.2 kg/cm2 (100 psi) static compaction whereas those samples above the optimum moisture content were prepared with 1 kg/cm2 static compaction.

For a given compaction effort, the coefficient of permeability was lowest when the sample was compacted near the optimum moisture content and decreased with increasing compaction effort.

3.1.3.5 Compressibility and Consolidation Characteristics

The effects of curing time and fly ash to filter cake ratios on the compressibility and consolidation characteristics of stabilized FGD sludge were studied and the results are summarized in Table 3-5. Parametric studies on the effect of lime content were not conducted, but it was anticipated that the addition of lime can reduce the compressibility to a certain extent.

The samples tested were prepared by statically compacting the FGD filter cakes at natural moisture content with a compactive effort of 1 kg/cm2. Selected samples were cured by means of constant-moisture curing for evaluating the effect of curing time.

3.1.3.5.1 Compressibility Characteristics

Compressibility characteristics are described in terms of the compressibility ratio. The higher the compressibility ratio, the more compressible is the material.

In general, the compressibility ratio of the stabilized sludge decreased with increasing fly ash to filter cake ratios and longer curing time.

Stabilized sludge cured for 28 days in constant-moisture conditions was consistently less compressible than the uncured stabilized sludge.

No consistent curing effect on the coefficient of secondary compression was observed and changes which did occur were relatively insignificant (Fox et al, 1982).

3.1.3.5.2 Consolidation Characteristics

The coefficient of consolidation, cv, is a measure of the rate at which the sludge will undergo primary consolidation, which is normally determined by the Terzaghi's or Taylor's methods. A typical void ratio vs log time curve is shown in Figure 3-11. It can be seen that most of the deformation occurred in the first 6 seconds after load application, which implies that the time for

the primary consolidation to occur was very small. After 6 seconds, the void ratio versus log time curves as shown in the figure are essentially linear as would be expected for secondary consolidation to take place.

It was estimated that the coefficient of consolidation of the stabilized sludge varies from 0.15 to 0.03 cm2/sec.

The coefficient of secondary compression decreased with increasing solids content from values of 1.5 to 1.0% for unstabilized filter cake at 35 to 50% solids content to 0.20 to 0.40% for cured stabilized filter cake at 60 to 70% solids content.

For estimating secondary compression settlements of cured stabilized sludge with 3.0% lime, a coefficient of secondary compression of 0.3% is considered representative.

3.2 PHYSICAL AND CHEMICAL PROPERTIES OF POND MIX STABILIZED LSDA SLUDGE

3.2.1 General

In order to study the behaviours of the sludge as disposed in the field, samples of pond mix stabilized LSDA sludge were obtained from the landfill for index testing and comparison to similar laboratory prepared mixes.

The pond mix was mixed at the plant and hauled to the pond in dump trucks.

The pond mix consisted of filter cake at 40 to 45% solids content, a fly ash to filter cake ratio of 0.8 and lime content of 3.0 to 4.0%. The stabilized mix was mixed at the plant and hauled to the ponds in dump trucks.

3.2.2 Index Properties

The index properties of the pond mix sludge are summarized in Table 3-1. They generally fall within the range of the properties of the laboratory prepared samples.

3.2.3 Shear Strength Characteristics

3.2.3.1 Isotropically Consolidated Drained Triaxial Tests

The specimens were prepared by statically compacting the pond mix at the natural moisture content approximately 30 days after sampling and allowed to cure for 28 days under constant-moisture conditions prior to testing.

The undrained effective stress paths, Mohr-Coulomb parameters and undrained stress-strain behaviour for cured pond mix stabilized LSDA sludge are given in Figures 3-12 and 3-13. The effective cohesion and effective angle of internal friction were 6.9 kN/m^2 (0.07 kg/cm^2) and 42.8 respectively. The slightly higher shear strength is probably because the sample was already one month old when prepared such that time dependent pozzolanic reactions between fly ash and lime were partially complete.

3.2.3.2 Unconfined Compression Tests

The specimens for the unconfined compression tests were prepared by statically compacting the pond mix sample at the natural water content approximately 30 days after sampling and allowed to cure for 7, 14 and 28 days under constant-moisture conditions prior to testing.

It was reported that curing time produced no significant strength gain on the unconfined compression strength, which was also slightly lower than that measured on laboratory prepared samples.

3.2.4 Permeability

The specimens were prepared similar to those for the shear strength test.

The coefficient of permeability varied from 1.6×10^{-5} cm/sec at a solids content of 58.8% to 7.0×10^{-6} cm/sec at 63.0% which were approximately three times as high as those measured on cured laboratory samples and similar to those of the uncured samples. It was explained that the sample was one month old when prepared and time-dependent pozzolanic reactions between the fly ash and lime were already partially complete. Remoulding the sample during specimen preparation might have disturbed the interaction between the particles hence giving higher permeability than expected.

CHAPTER 3

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TABLE 3-1

INDEX PROPERTIES OF FILTER CAKE, FLY ASH, LIME AND POND MIX STABILIZED FGD SLUDGE FOR THE LSDA PROCESS AT PLANT SCHOLZ (FOX et al, 1982)

Sample	Field Sampling Date	Average Moisture Content, w_n (%)	Average Solids Content, S (%)	pH	Specific Conductance, G (μmhos/cm)	Liquid Limit, LL (%)	Specific Gravity G_s	Particle Size -74 μm (%)	Particle Size -2 μm (%)
Filter Cake	3-27-81	121.1	45.2	4.3	24,000	34	2.55	100	28
Fly Ash	3-27-81	0.14	99.86	3.5	7,600	-	2.55	95	4
Lime	3-27-81	0.0	100.0	13.0	7,800	-	2.27	-	-
Pond Mix FGD Sludge	3-27-81	66.8	60.0	12.3	29,000	-	2.60	96	26
Pond Mix FGD Sludge	4-10-81	53.7	65.1	11.6	33,500	-	-	-	-
Pond Mix FGD Sludge	4-13-81	50.9	66.3	10.6	22,500	-	-	-	-
Pond Mix FGD Sludge	4-16-81	47.8	67.7	11.0	21,000	42	2.69	93	27

TABLE 3-2

INDEX PROPERTIES OF LABORATORY MIX STABILIZED LSDA SLUDGE FROM PLANT SCHOLZ (FOX et al, 1982)

Filter Cake Solids Content (%)	Fly Ash to Filter Cake Ratio (%)	Lime Content (%)	Moisture Content (%)	Solids Content (%)	pH	Specific Conductance (μmhos/cm)	Liquid Limit (%)	Specific Gravity	Particle Size <74 μm (%)	Particle Size <2 μm (%)
47	0.75	3	62.6	61.5	12.6	31,000	51.3	2.67	99	27
47	1.00	1	55.8	64.2	7.9	26,500	39.3	--	--	--
47	1.00	3	54.8	64.6	12.7	31,000	49.5	2.65	100	20
47	1.00	5	53.6	65.1	12.7	21.600	51.9	--	--	--
50	0.80	5	52.9	65.4	12.7	21,750	54.0	--	--	--
56	0.75	1	44.5	69.2	9.2	16,000	44.4	--	--	--
56	0.75	3	43.7	69.6	12.4	27,000	45.4	2.61	99	26
56	0.75	5	42.9	70.0	12.7	18,750	45.6	--	--	--
56	1.00	3	38.1	72.4	12.1	23,500	50.0	2.68	99	9

TABLE 3-3

COMPARISON OF DRY DENSITIES OF STABILIZED LSDA SLUDGE AT NATURAL WATER CONTENT AND OPTIMUM WATER CONTENT (FOX et al, 1982)

Solids Content (% of Filter Cake)	Fly Ash to Filter Cake Ratio	Measured Natural Water Content %	Predicted Actual Dry Density at kg/m^3	Predicted Optimum Water Content %	Predicted Maximum Dry Density kg/m^3
47	0.75	62.6	995	26.5	1466
47	1.00	65.8	1078	36.5	1280
56	0.75	47.7	1226	26.5	1466
56	1.00	38.1	1264	36.5	1280

TABLE 3-4

SUMMARY OF MOHR-COULOMB
EFFECTIVE STRESS STRENGTH PARAMETERS FOR
CURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ)
(FOX et al, 1982)

Sample Description*			Mohr-Coulomb Failure Criterion	
S_c (%)	R	L (%)	$\bar{c}$ (kg/cm^2)	$\bar{\phi}$
47	0.75	3.0	0.61	37.5°
47	1.00	3.0	0.73	39.0°
56	0.75	1.0	0.35	39.9°
56	0.75	3.0	0.82	36.8°
56	0.75	5.0	3.49	36.7°
56	1.00	3.0	0.88	39.3°

*Samples statically compacted at natural moisture content in three equal lifts with load of 1.0 kg/cm^2 maintained for 60 seconds per lift and cured in constant-moisture conditions for 28 days.

TABLE 3-5

SUMMARY OF UNTREATED AND TREATED LSDA SLUDGE

(Fox et al, 1982)

	PROPERTIES	UNIT	UNTREATED SLUDGE	TREATED SLUDGE						POND MIX
				Fly Ash (by wt.)-.75 Filter Cake			Fly ash (by wt.)-1.00 Filter Cake			
				Lime % 1	Lime % 3	Lime % 5	Lime % 1	Lime% 3	Lime % 5	
Morphology	Mineral Composition	-	2/3 sulfite 1/3 sulfate							
INDEX PROPERTIES	Particle Size Distribution	%<74 m	100	-	99	99*	-	100	-	93-100
		%<2 m	28	-	27	26*	-	20	-	4-28
	Specific Gravity	-	2.55	-	2.67	2.61*	-	2.65	-	2.60-2.69
	Solid Content (Filter Cake)	%	45	69.2*	61.5	69.6*	64.2	64.6	65.1	60-67.7
	Natural Water Content (Filter Cake)	%	121	44.5*	62.6	42.9*	55.8	54.8	53.6	47.8-66.8
	Bulk Density (Filter Cake)	Kg/m^3	1380	1740+	1625	1760	1653+	1670	1670+	1580-1770
	Liquid Limit	%	34	44.4*	51.3	45.4*	39.3	49.5	51.9	42
	Plastic Limit	%	Non-Plastic	-	-	-	-	-	-	-
	Specific Conductance	m hos/	74,000	16,000*	31,000	27,000*	26,500	31,000	21,600	21,000-33,500
	pH	-	4.3?	9.2*	12.6	12.4*	7.9	12.7	12.7	10.6-12.3

(CV13)

TABLE 3-5 Continued

	PROPERTIES	UNIT	UNTREATED SLUDGE	TREATED SLUDGE						POND MIX
				Fly Ash (by wt.)=.75 Filter Cake			Fly ash (by wt.)=1.00 Filter Cake			
				Lime % 1	Lime % 3	Lime % 5	Lime % 1	Lime% 3	Lime % 5	
Compaction	Standard Max. Pd	Kg/m^3	1680	-	-	-	-	-		1250-1000
	Proctor Wopt	%	15	-	-	-	-	-		35-25
	Sopt	%	87	-	-	-	-	-		
Charac-teristics	Static Max. Pd	Kg/m^3	1570	-	1470	-	-	1280	-	
	Com-paction Wopt	%	17	-	26.5	-	-	36.5	-	
	100 psi Sopt	%	85.5	-	79.1	-	-	73.2	-	
Shear Strength	c' +	KN/m^2	-	34*	60	342*	-	72	-	6.9
	Ø' +	degree	-	39.9*	37.3	36.7*	-	39	-	42.8
	Qu **	KN/m^2	46-103	60*	164	787*	67	276	1223	98-294
Permeab-ility	K x 10^{-6}	cm/sec.	4 - 38	1.9 - 2.8*	2.6 - 3.1	0.11 - 0.021*	4.7 - 6.6	1.2 - 2.5	0.27 - 0.085	7-16
Charac-teristics	Corresponding Pd	Kg/m^3	880 - 1080	1239 - 1292*	947 - 1077	1110 - 1346	1176 - 1210	1030 - 1220	1096 - 1208	--
	Corresponding Sc	%	26.2 - 64.9	69.9 - 71.5*	59.3 - 64.4	66.7 - 73.2	67.9 - 68.9	62.7 - 69.3	63.8 - 68.9	63-58.8
Consol-idation Character-istics	Compression Index	-	0.25-0.3		0.016 - 0.12			0.002 - 0.10		
	Coef. of Primary Consol	cm^2/sec	0.1		0.15 - 0.03			0.15-0.03		
	Coef. of Second. Compression	%	0.59 - 1.00		0.11 - 0.27			0.21 - 0.35		

* Solids content of the filter cake sample is 56% (others are 47%)

+ Samples statically compacted and cured in constant moisture for 28 days

** Samples cured at constant moisture at 28 days

(CV13)

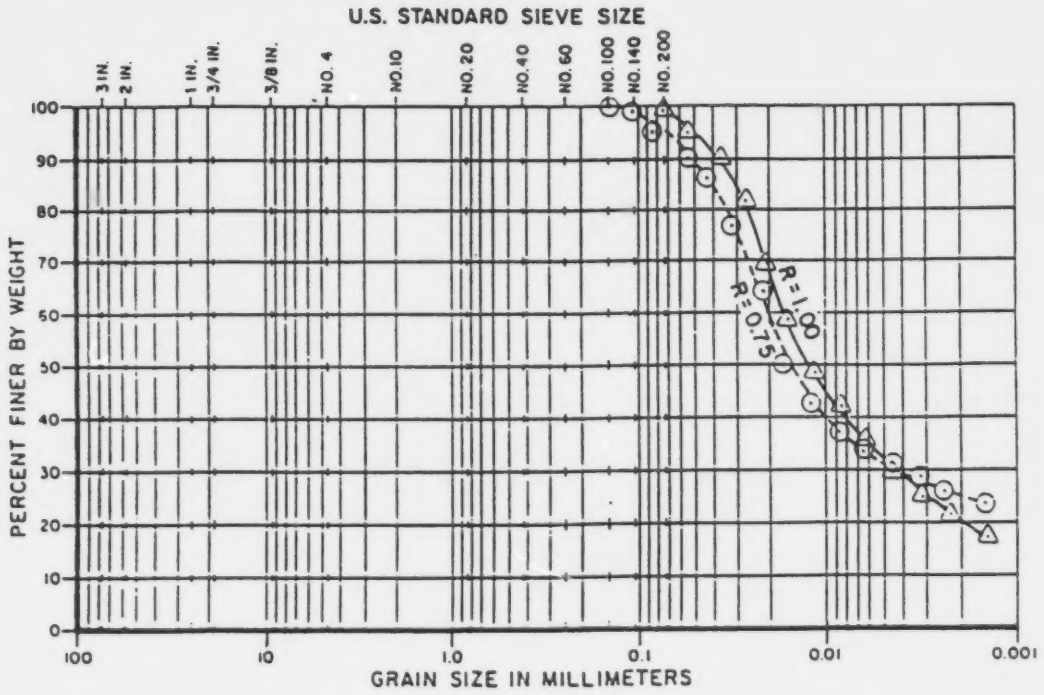


FIGURE 3-1

PARTICLE SIZE DISTRIBUTION OF STABILIZED LSDA SLUDGE WITH S_c=47% AND L = 3.0% (FOX et al, 1982)

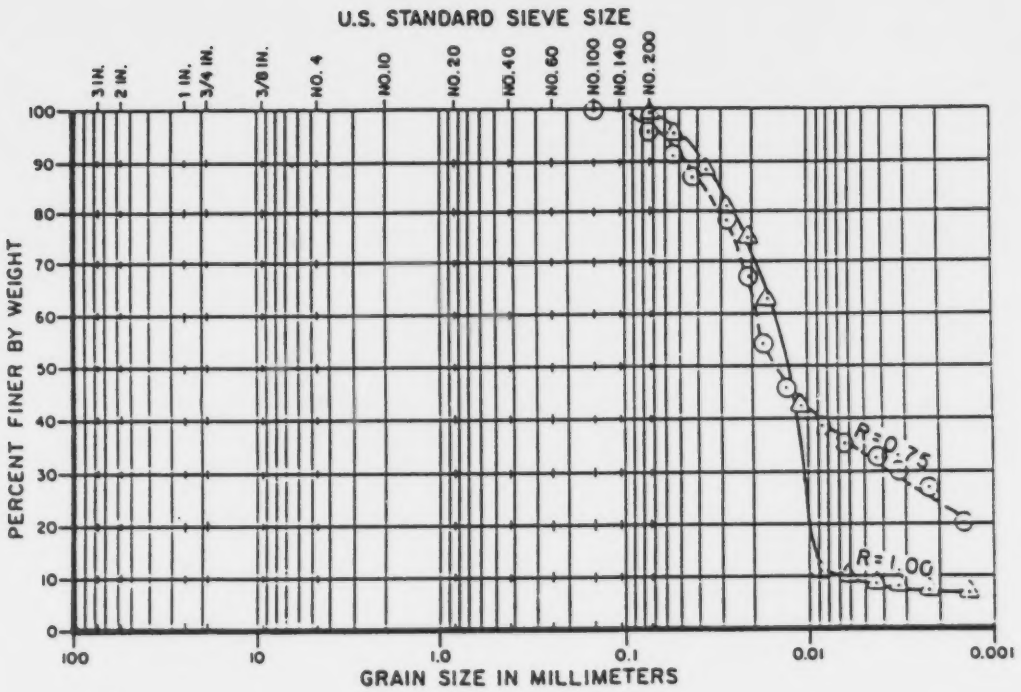
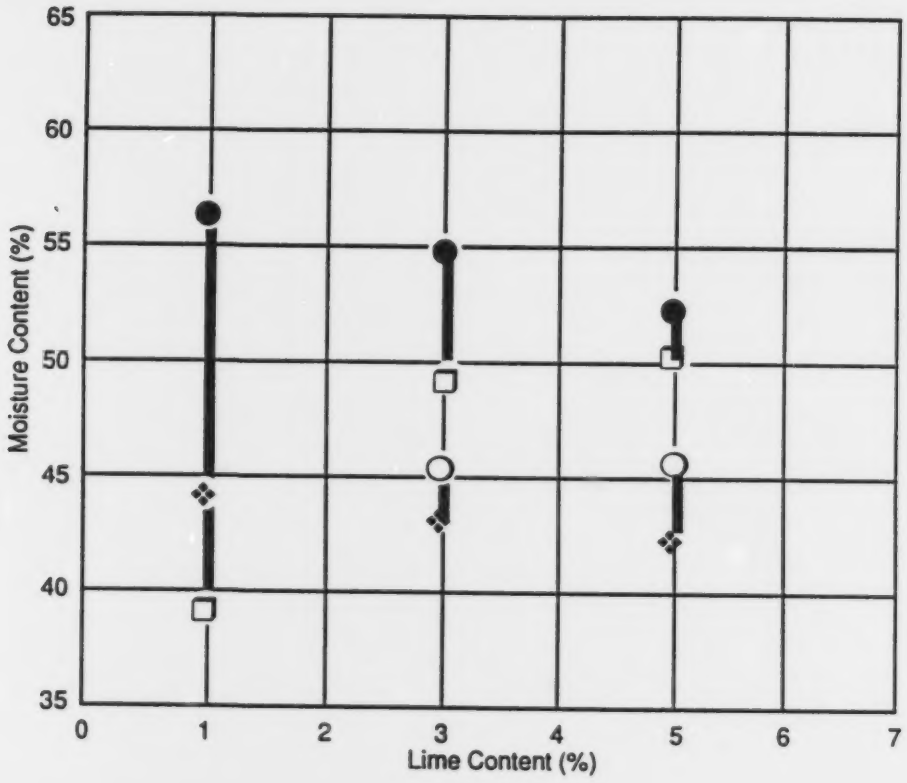


FIGURE 3-2

PARTICLE SIZE DISTRIBUTION OF STABILIZED LSDA SLUDGE WITH S_c= 56% AND L = 3.0%

(FOX et al, 1982)



Legend

- Natural Moisture Content of mix Stabilized LSDA Sludge with Solids Content = 47% and Fly Ash to Filter Cake Ratio = 1
- Natural Moisture Content of mix Stabilized LSDA Sludge with Solids Content = 56% and Fly Ash to Filter Cake Ratio = 0.75
- Liquid Limit of mix Stabilized LSDA Sludge with Solids Content = 47% and Fly Ash to Filter Cake Ratio = 1
- Liquid Limit of mix Stabilized LSDA Sludge with Solids Content = 56% and Fly Ash to Filter Cake Ratio = 0.75

FIGURE 3-3
MOISTURE CONTENT VS LIME CONTENT
(FOX et al, 1982)

179031-RD
KNARF 8

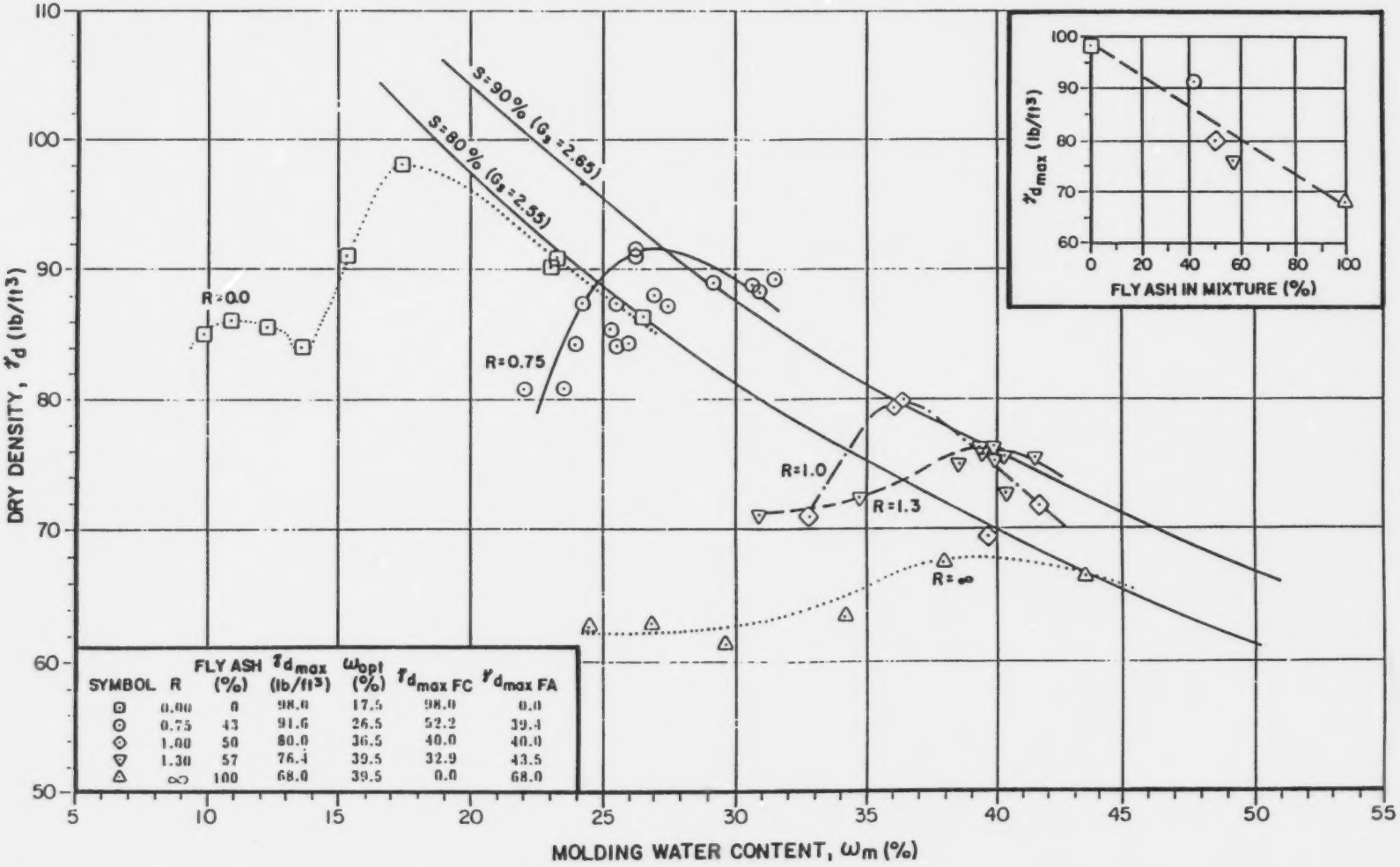

DRY DENSITY, γ_d (lb/ft³)
MOLDING WATER CONTENT, ω_m (%)
S=90% (G_s=2.65)
S=80% (G_s=2.55)
R=0.0
R=0.75
R=1.0
R=1.3
R=∞
$\gamma_{d_{max}}$ (lb/ft³)
FLY ASH IN MIXTURE (%)
SYMBOL R FLY ASH (%) $\gamma_{d_{max}}$ (lb/ft³) ω_{opt} (%) $\gamma_{d_{max}}$ FC $\gamma_{d_{max}}$ FA
0.00 0 98.0 17.5 98.0 0.0
0.75 43 91.6 26.5 52.2 39.4
1.00 50 80.0 36.5 40.0 40.0
1.30 57 76.4 39.5 32.9 43.5
∞ 100 68.0 39.5 0.0 68.0

FIGURE 3-4

MOLDING WATER CONTENT VERSUS DRY DENSITY FOR 100 psi STATIC COMPACTION EFFORT - LSDA SLUDGE FROM PLANT SCHOLZ (FOX ET AL, 1982)

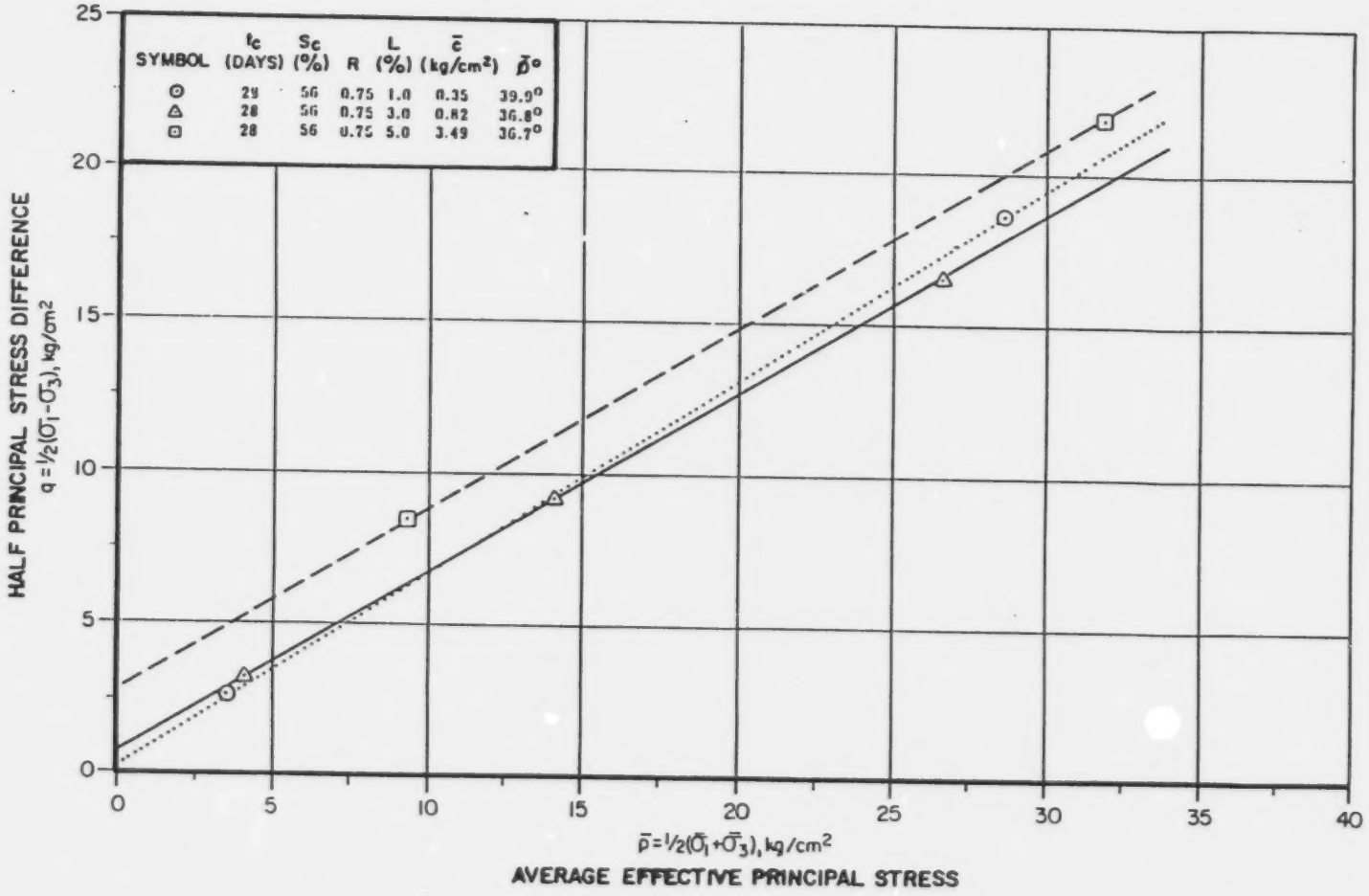


FIGURE 3-5

COMPARISON OF MOHR-COULOMB PARAMETERS FOR CURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ) WITH S_c= 56%, R = 0.75 AND L = 1.0, 3.0 AND 5.0%
(FOX et al, 1982)

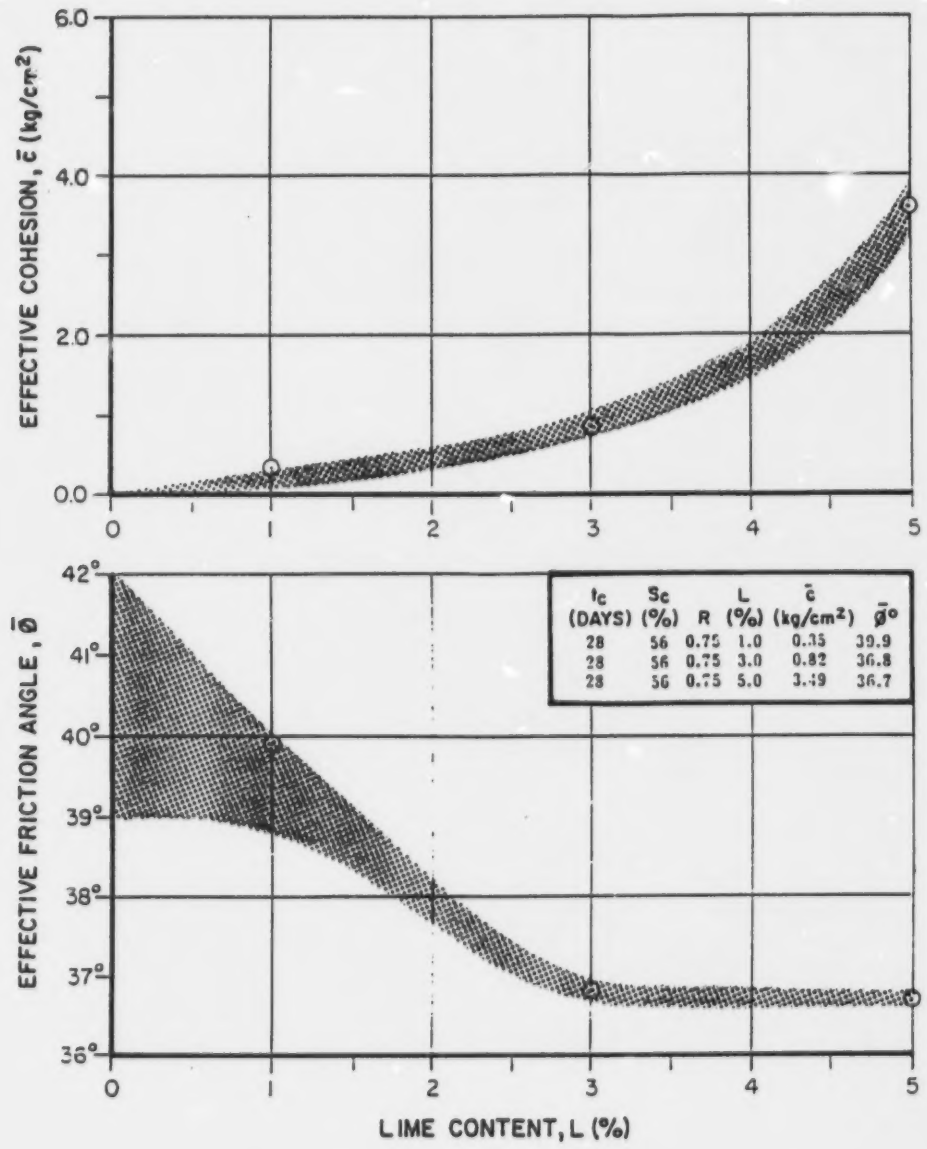


FIGURE 3-6

EFFECT OF LIME CONTENT ON EFFECTIVE COHESION AND FRICTION ANGLE OF CURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ) (FOX et al, 1982)

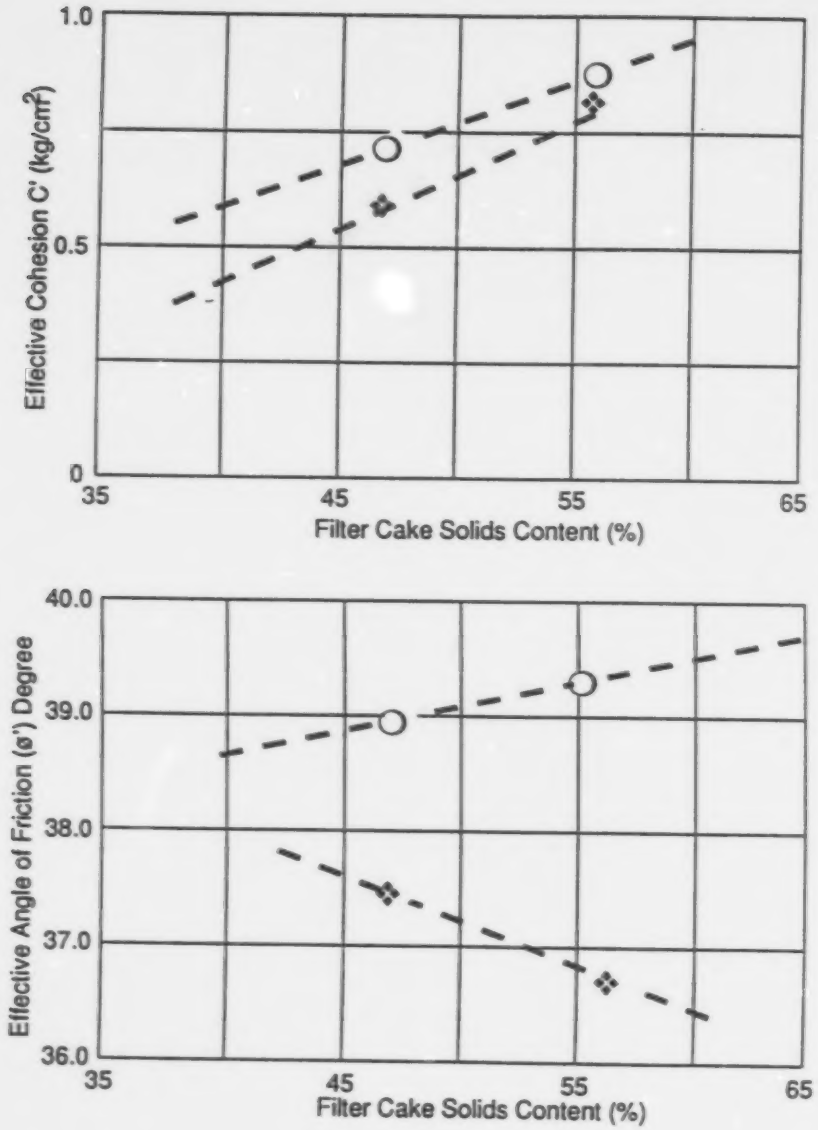


FIGURE 3-7
C' AND Ø' VS SOLIDS CONTENT OF STABILIZED LSDA SLUDGE (PLANT SCHOLZ) (FOX et al, 1982)

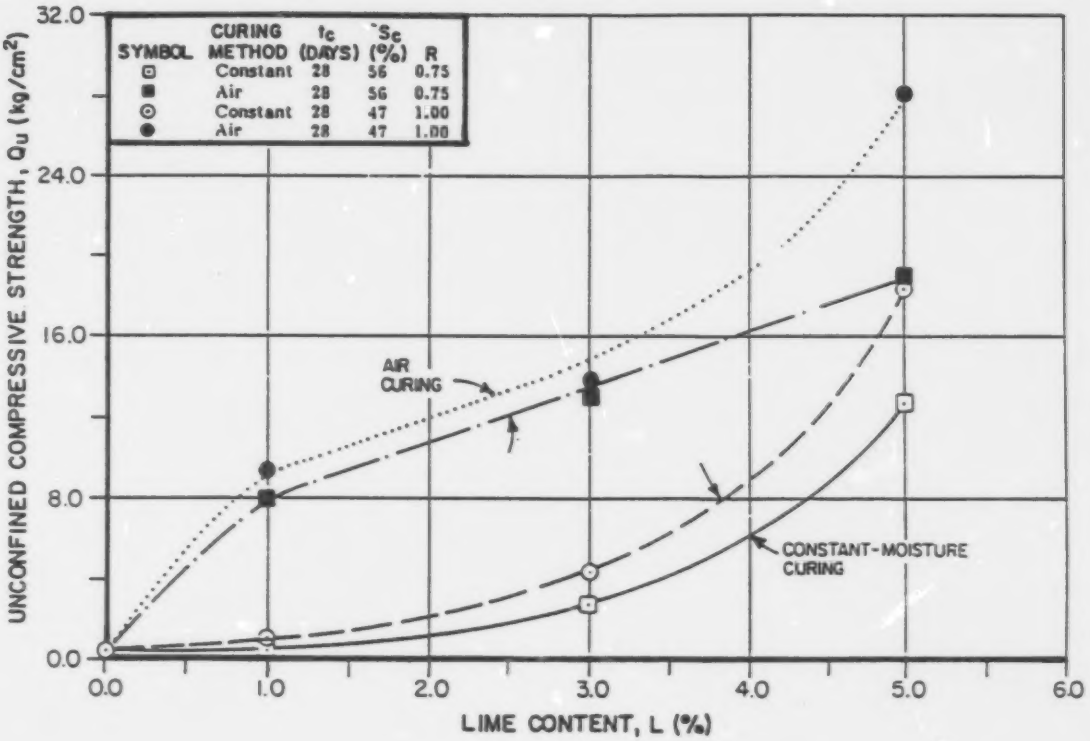
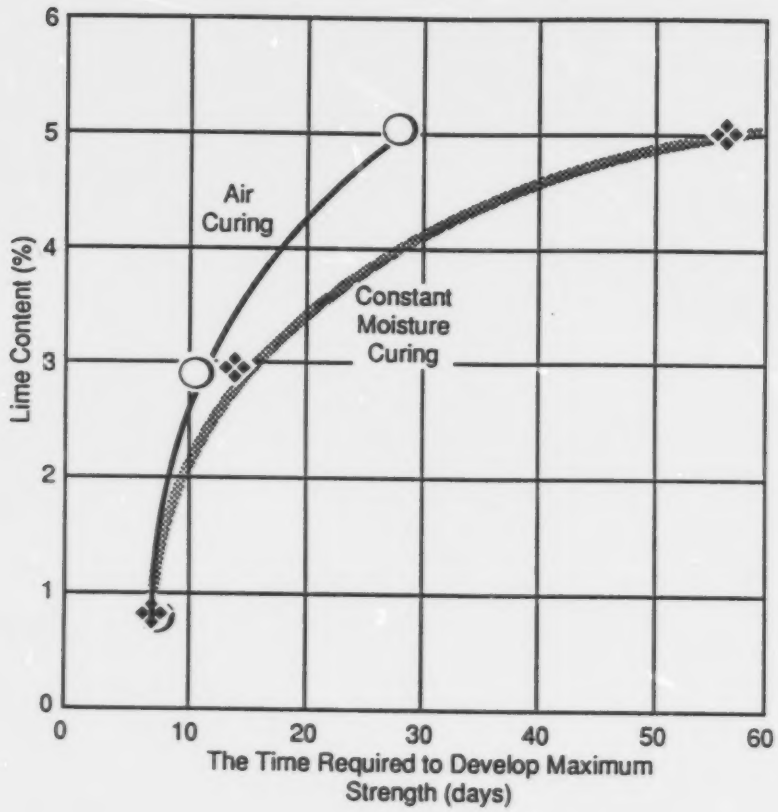


FIGURE 3-8

EFFECT OF LIME CONTENT AND WIRING ENVIRONMENT ON UNCONFINED COMPRESSIVE STRENGTH OF CURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ) (FOX et al, 1982)



Solids Content = 56%
Fly Ash to Filter Cake Ratio = 0.75

FIGURE 3-9
LIME CONTENT VS TIME REQUIRED TO DEVELOP MAXIMUM UNCONFINED COMPRESSION STRENGTH OF STABILIZED LSDA SLUDGE (PLANT SCHOLZ) (FOX et al, 1982)

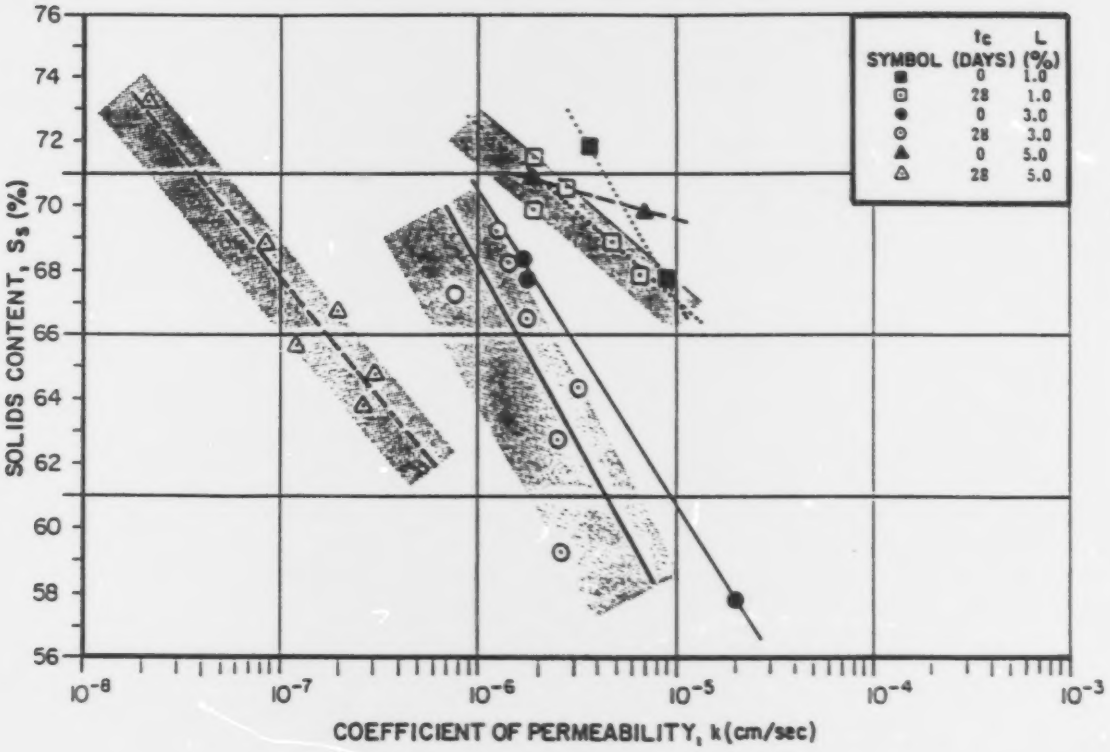


FIGURE 3-10

EFFECT OF CURING TIME ON COEFFICIENT OF PERMEABILITY OF STABILIZED LSDA SLUDGE (PLANT SCHOLZ) (FOX et al, 1982)

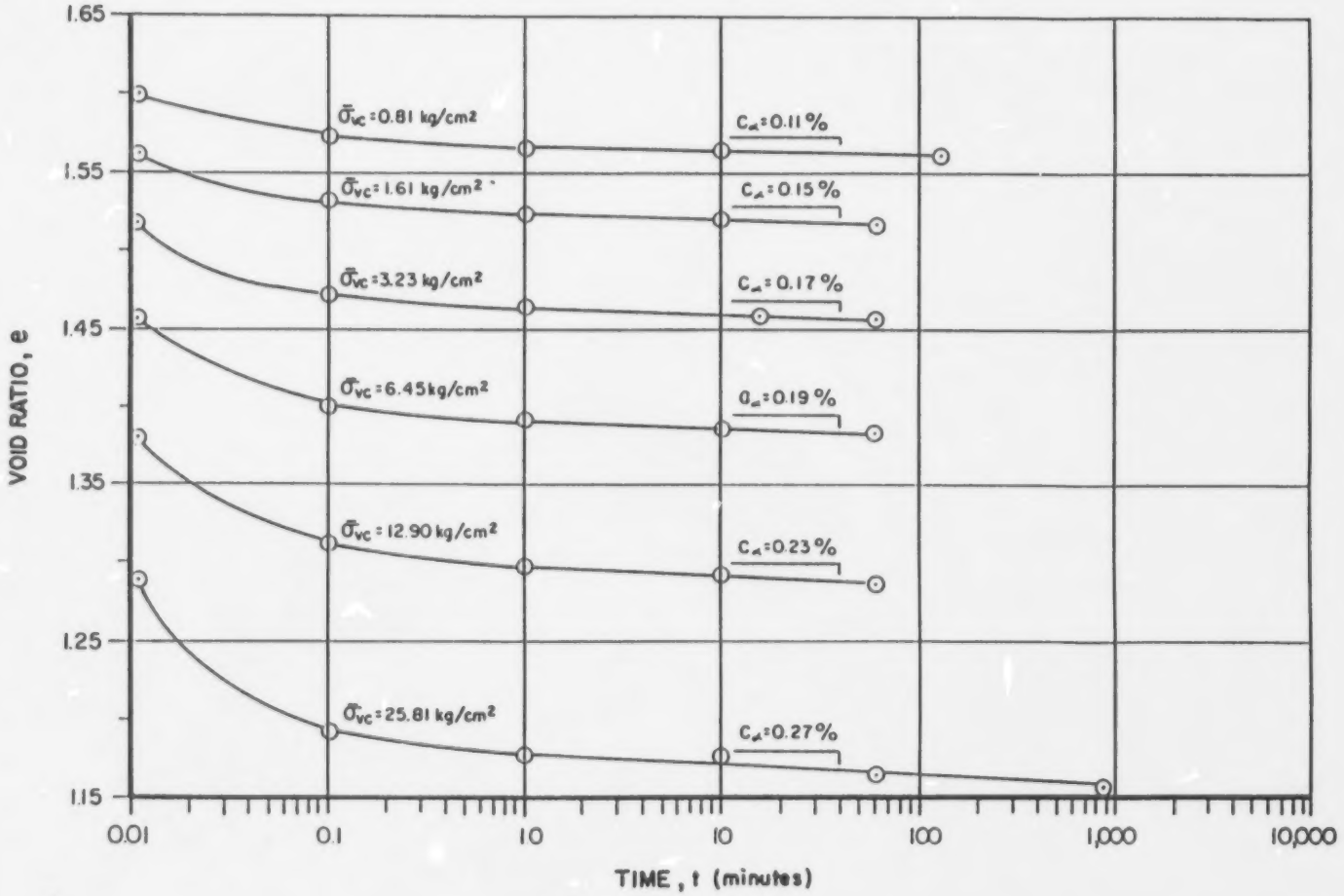


FIGURE 3-11

TYPICAL VOID RATIO VERSUS TIME CONSOLIDATION CURVES FOR UNCURED STABILIZED LSDA SLUDGE (PLANT SCHOLZ) WITH S_C= 47%, R = 0.75 AND L = 3.0%
(FOX et al, 1982)

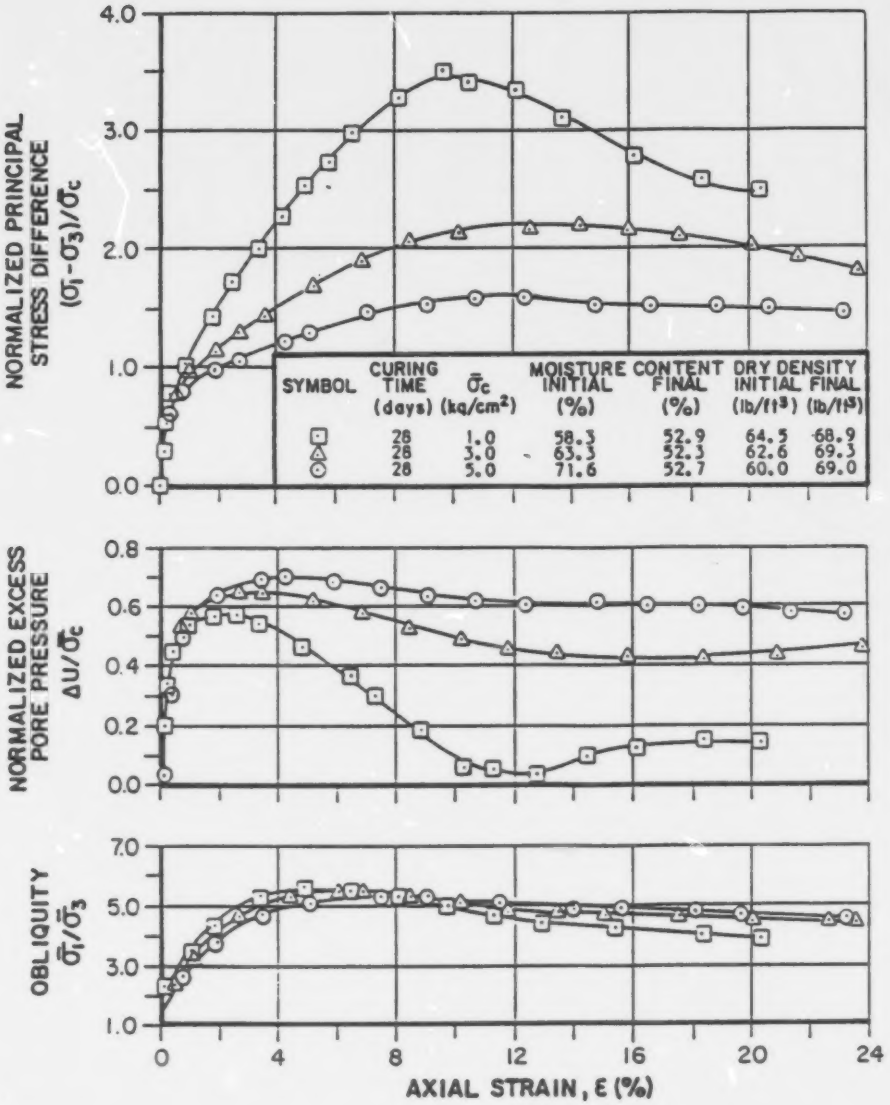

NORMALIZED PRINCIPAL STRESS DIFFERENCE $(\sigma_1-\sigma_3)/\bar{\sigma}_c$
NORMALIZED EXCESS PORE PRESSURE $\Delta U/\bar{\sigma}_c$
OBLIQUITY $\bar{\sigma}_1/\bar{\sigma}_3$
AXIAL STRAIN, ε (%)
SYMBOL
CURING TIME (days)
$\bar{\sigma}_c$ (kg/cm²)
MOISTURE CONTENT INITIAL (%)
MOISTURE CONTENT FINAL (%)
DRY DENSITY INITIAL (lb/ft³)
DRY DENSITY FINAL (lb/ft³)
28 1.0 58.3 52.9 64.5 68.9
28 3.0 63.3 52.3 62.6 69.3
28 5.0 71.6 52.7 60.0 69.0

FIGURE 3-12

UNDRAINED STRESS-STRAIN BEHAVIOR OF CURED POND MIX STABILIZED LSDA SLUDGE (PLANT SCHOLZ) (FOX et al, 1982)

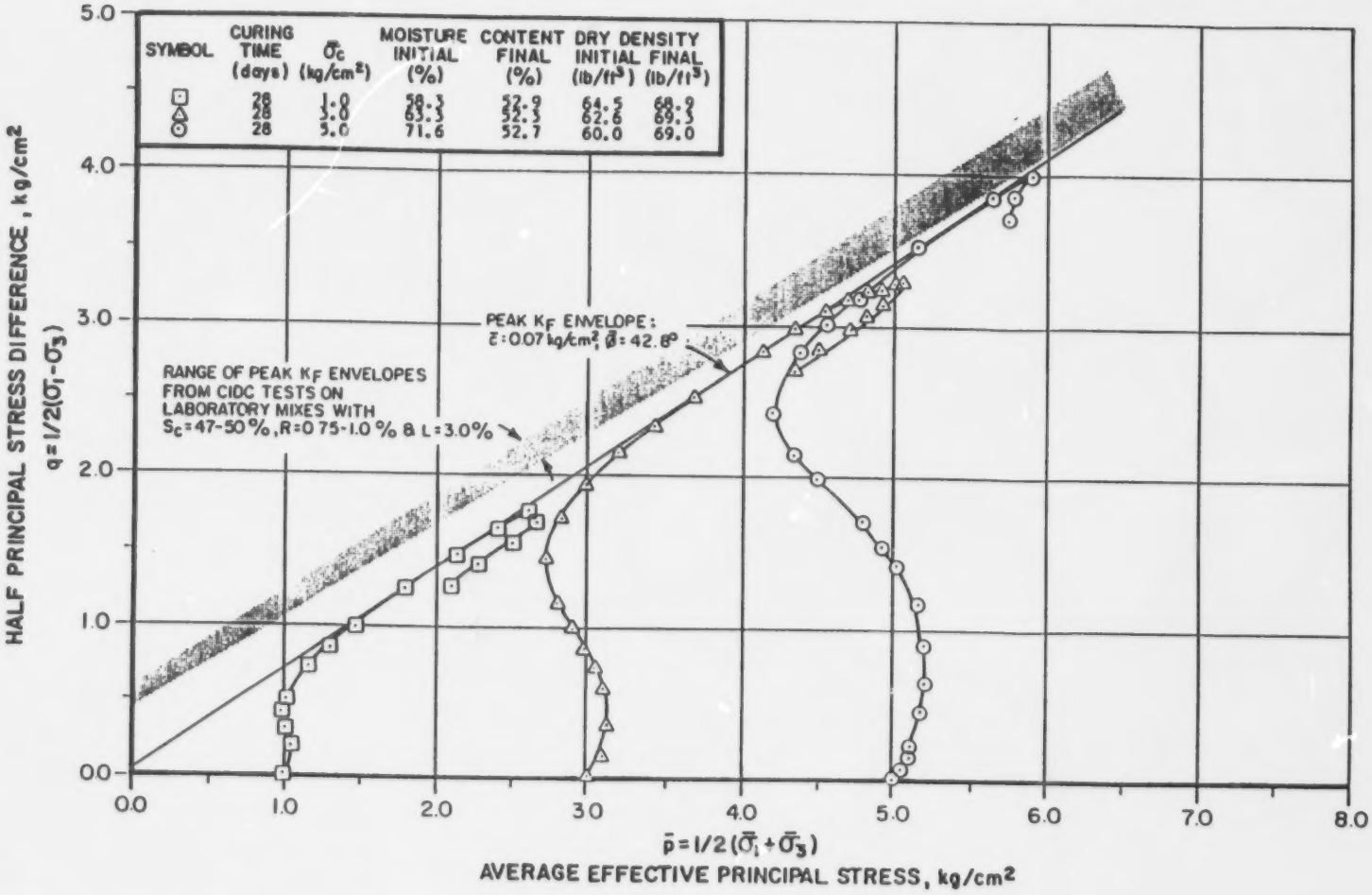


FIGURE 3-13

UNDRAINED EFFECTIVE STRESS PATHS AND MOHR-COULOMB PARAMETERS FOR CURED POND MIX STABILIZED LSDA SLUDGE (PLANT SCHOLZ) (FOX et al, 1982)

4.0 ENGINEERING CHARACTERISTICS OF STABILIZED LDA SLUDGE/FILTER CAKE

4.1 General

The engineering properties of FGD sludge are highly variable and are influenced by the characteristics of the sorbent, and quality of the coal, and the methodology of the scrubbing process.

In general, as-produced sludges cannot be effectively compacted due to their high water content and low shear strength. They must be adequately dewatered or mixed with dry additive to increase the solids content and to lower the water content to close to the optimum so that they can be compacted effectively.

Fly ash and lime are usually used to provide stabilization and fixation to the sludge. Besides adding solids content to the sludge, the fly ash can react with added lime or the lime already present in the sludge to form bond, which has been observed to have significant effects on compressibility, shear strength and permeability of the sludge (Hagerty et al, 1977, Krizek, 1979, and Rossoff et al, 1979).

Hagerty et al, (1977) summarized the geotechnical properties of six FGD sludges generated from lime dual alkali, wet lime and wet limestone scrubbing FGD processes and the effect of stabilization and fixation on the properties of these sludges.

Krizek, (1979) described several alternative management schemes for a landfill composed of FGD sludge generated from the patented FMC Corporation dual alkali FGD system. The schemes were developed on the basis of information and experience gained from an extensive 3-year program.

Rossoff et al, (1979) also summarized the geotechnical properties of a number of treated and untreated FGD sludges and evaluated the leachate characteristics of the sludge that had been disposed of by landfilling.

Krizek et al, (1987) collected and summarized extensive test data from more than a decade of research on the geotechnical properties of FGD sludges with emphasis on untreated and treated dual alkali sludges.

It is attempted in this section to summarize the characteristics of the stabilized and fixated LDA sludges as related to their disposal and utilization.

4.2 Physical Properties

4.2.1 Mineralogy and Composition

The sludges produced from the FMC LDA process was described to have the appearance of a clayey silt (Krizek et al, 1977).

The FMC filter cake is mainly composed of calcium sulfite, calcium sulfate and some calcium carbonate as shown in Table 4-1. The interstitial water contains soluble residues of lime, sodium sulfate and sulfite salts and chloride salts.

The sulfite and sulfate crystals of the LDA sludge are chemically similar to those generated from the wet lime and limestone scrubbing process but the crystal structure is markedly different. The LDA sludge is composed of particles having a leafy rosette structure.

Rossoff et al, (1979) reported that untreated LDA sludge from GPS Scholz plant was comprised of very fine particulates agglomerated in clusters. Cluster size ranged from individual particles up to agglomerates as large as 50 μm in diameter. Most agglomerates, however, were about 10 μm to 20 μm in diameter. The clusters appeared to have formed randomly. The samples mixed with fly ash had sulfur phase agglomerates identical to the plain sludge. In addition, there were fly ash particles in the range of 10 μm to 20 μm diameter.

4.2.2 Index Properties

The index properties of some stabilized LDA sludges are given in Table 4-2 and are briefly described below.

4.2.2.1 Particle Size Distribution

The LDA sludges are composed of uniform silt size material. The particle size distribution of typical LDA sludge, as determined from hydrometer tests is shown in Figure 4-1.

4.2.2.2 Specific Gravity

As shown in Table 4-2, the specific gravity of the LDA sludge is about 2.50 which is typical for sulfite-rich sludge. The sulfate-rich sludges have comparatively lower value of specific gravity (Krizek et al, 1987).

4.2.2.3 Water Content

Krizek, (1979) reported that the water content of a stabilized LDA sludge from Illinois station was about 49%. The water content of FMC sludge was reported to be about 26.5% as shown in Table 4-2.

4.2.2.4 Atterberg's Limits

The liquid and plastic limits of untreated LDA sludges were reported to be 45% and 34% (Krizek, 1979). The FMC sludges were reported to be non-plastic.

4.2.2.5 pH

The pH controls the chemical solubility of trace metals and the variation of the physical properties of the sludges.

It was reported that the pH of a LDA sludge at a water to solid ratio of approximately two yielded value greater than 12 (Krizek et al, 1987).

4.2.3 Compaction Characteristics

The water contents of the as-produced sludges are usually much higher than their optimum water content and therefore the maximum dry densities obtained in the laboratory cannot be obtained in the field. The addition of fly ash and lime can result in higher solids content and bring the water content closer to the optimum.

Hagerty et al, (1977) pointed out that the addition of fly ash could change the compaction characteristics of the sludge. Typical moisture-density relation of LDA sludges and other FGD sludges are presented in Figure 4-2 and also in Table 4-3.

The addition of fly ash decreased the maximum dry density but increased the optimum water content.

Krizek et al, (1987) pointed out that remoulding the materials and increasing the compactive energy could yield higher density if the water content was close to optimum but would have no effect if the water content was higher than the optimum water content.

4.2.4 Shear Strength Characteristics

The shear strength characteristics of typical sulfite-rich sludges resemble those of micaceous silts and very fine sand (Hagerty et al, 1977).

The shear strength characteristics of LDA sludges had been evaluated by means of consolidated drained triaxial tests, consolidated undrained compression tests, consolidated direct shear tests, unconfined compression tests and load bearing tests, and the results are summarized below. The effect of fly ash and lime content, curing time and curing environment will also be discussed.

4.2.4.1 Consolidated Drained and Undrained Triaxial Tests

The effects of sludge stabilization and fixation on the effective shear strength parameters of LDA sludge are shown in Table 4-4.

Unstabilized samples compacted at their as-produced water contents showed that the shear strength was largely governed by frictional phenomenon.

Without any curing, addition of fly ash had little influence on the effective shear strength parameters although effective cohesion was slightly increased. However, samples cured under constant moisture conditions for as little as 14 days could increase the effective angle of internal friction by several degrees and the effective cohesion many folds. The increase was attributed to the pozzolanic reaction of the lime and the other components in the mixture (Krizek et al, 1987).

There is limited information available on the undrained shear strength of stabilized sludge. It was reported that adding fly ash on cured samples did not affect the angle of internal friction. However, the angle of friction increased 3 degrees when 1% or 2% of lime was added to the mixture (Krizek et al, 1987).

Consolidated direct shear tests on samples compacted at their as-produced water content yielded negligible cohesion and a slightly higher angle of internal frictions of 35° - 40° as compared to that obtained by the triaxial compression test (Krizek, 1979).

4.2.4.2 Unconfined Compression Tests

Unconfined compression tests were carried out on unstabilized and stabilized sludge at various fly ash, lime and additive content and curing time. The samples were prepared by compacting the mixture at optimum water content and allowed to dry slowly in a controlled moisture room (Hagerty et al, 1977). The results are presented in Table 4-5.

It was observed that adding fly ash in increasing amounts decreased the strength of the mixture as shown in Figure 4-3. As shown in the figure, highest strength could be obtained with 40% - 60% of fly ash content.

The effect of lime content on the unconfined compression strength is summarized in Figure 4-4. Krizek et al, (1987) pointed out that the strength gained by adding fly ash and lime depended on the number of contacts between fly ash particles and lime particles in the mix. It was reported that a uniformly graded lime with particle size around 0.2 mm seemed to have a stronger effect on strength gain than well-graded lime (Krizek et al, 1987).

The unconfined compression strength increased with decreasing water content as shown in Figure 4-5.

Krizek et al, (1987) concluded that longer curing time could increase the shear strength of both treated and untreated LDA sludge.

The addition of cement significantly increased the unconfined compression strength and the strength increased with longer curing time as shown in Table 4-5.

4.2.4.3 Load Bearing Test

Rossoff et al, (1979) described the use of the standard load bearing test on evaluating the bearing strength of FGD sludges in which a 0.95 cm diameter rod was forced into the sludge at a constant rate of 0.25 cm/min with an Instron loading machine. Penetration loads were recorded continuously to a maximum penetration depth of 2.54 cm. 1.27 cm and 2.54 cm diameter rods were also used to confirm that the effect of rod size was not significant. The specimens tested were dewatered by means of underdraining.

The loads measured at the maximum penetration depth of 2.54 cm were plotted against the corresponding solid contents as shown in Figure 4-6.

It was observed that the load bearing strength increased with increasing solids content. The addition of fly ash increased the solids content, thereby increasing the shear strength. The LDA sludge generated from the Utah Power and Light (UPL) Gadsby station had higher shear strength than that generated from GPC Scholz station, indicating that the properties of the sludge varied from plant to plant.

4.2.5 Permeability

The coefficients of permeability obtained from laboratory tests ranged from $1x10^{-5}$ to $1x10^{-6}$ cm/sec and the Hazen empirical relationship of predicting permeability from particle size distribution is valid on the sludge (Krizek, 1979).

Adding fly ash to the sludge usually increases the coefficient of permeability but it usually remains within the same order of magnitude (Table 4-6). The addition of lime to a sludge-fly ash mixture generally decreased the permeability (Krizek et al, 1987).

In general, the coefficient of permeability of laboratory prepared LDA sludge decreased as water content and dry density decreased as summarized in Figure 4-7.

4.2.6 Compressibility and Consolidation Characteristics

4.2.6.1 Compressibility

The compressibility of the LDA sludge is evaluated in the laboratory by means of the conventional consolidation test for soil.

Hagerty et al, (1977) observed that oxidized sludges are less compressible than sulfite-rich sludges (Figure 4-8). It was also pointed out that samples compacted at optimal water content could reduce compressibility (Figure 4-9).

Krizek, (1979) reported that LDA sludge had a compressibility index of 0.75 which increased only slightly with increasing compaction energy. Some typical value of compression indices of LDA sludges are given in Table 4-7.

Addition of fly ash increased the solids content and hence reduced the compressibility of the sludge.

4.2.6.2 Consolidation Characteristics

Primary consolidation was observed to occur very fast which rendered estimation of the coefficient of consolidation impractical, and secondary consolidation was significant (Hagerty et al, 1977).

Krizek et al (1987) pointed out that the addition of lime to a fresh sludge-fly ash mixture might have little influence on the consolidation behaviour of the mixture. A compression indices of 0.75 and 1.05 were reported on an unstabilized sample and a mixture with 0.5 fly ash to filter cake ratio, respectively (Krizek, 1979).

Typical void ratio versus consolidation stress curves for a variety of sludges and some common soils are presented in Figure 4-8.

CHAPTER 4

REFERENCES

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TABLE 4-1

REPORTED MINERALOGY OF TYPICAL LDA SLUDGE

SOURCE OF SAMPLE	MINERALOGY	REFERENCE
Plant Scholz	73%* Calcium Sulfite 7% Calcium Sulfate 17% Calcium Carbonate	Hagerty et al, - 1977
Kentucky	Sulfite (Agglomerate Crystal)	Fox et al, 1982
FMC Unstabilized	83% { Calcium Sulfite and { Calcium Sulfate 7% $CaCo_3$ 10% { Sodium Sulfite { Sodium Sulfate Chloride	FMC, 1987
FMC Stabilized with Fly Ash	53% { Calcium Sulfite { Calcium Sulfate 4-5% $CaCo_3$ 3% Soluble Salt 36% Fly Ash	FMC, 1987
FMC Stabilized/Fixated with Fly Ash & Lime	51% { Calcium Sulfite & { Calcium Sulfate 4-3% $CaCo_3$ 3-6% Soluble Salt 35.2% Fly Ash 2-6% Lime	FMC, 1987

(CV12)

* % of dry weight

TABLE 4-2

INDEX PROPERTIES OF STABILIZED LDA SLUDGE

SOURCE OF SAMPLE	FLY ASH TO FILTER CAKE RATIO	LIME CONTENT %	MOISTURE CONTENT %	SOLIDS CONTENT %	LIQUID LIMIT %	SPECIFIC GRAVITY	PARTICLE SIZE DISTRIBUTION <74 m	<2 m	REFERENCE
Illinois (FMC)	1	0	49	67.1	Non Plastic	2.52	Silt	Size	Krizek, 1979
CEA/ADL	0	0	-	-	Non Plastic	2.56	94	6	Hagerty et al, 1977
	0.75	0	-	-		2.43	92	2	
	0.75	0	-	-		2.50	94	3	
FMC	0	0	36.3	73.4	Non Plastic	-	-	-	FMC, 1987
	0.5	0	26.6	79.0		-	-	-	
	0.5	2.5	26.1	79.3					

(CV13)

TABLE 4-3

MAXIMUM DRY DENSITY AND OPTIMUM
WATER CONTENT OF STABILIZED LDA SLUDGE

SOURCE OF SAMPLE	FLY-ASH TO FILTER CAKE RATIO	LIME CONTENT	COMPACTION CHARACTERISTICS		REFERENCE
			ρd Kg/m^3	W OPT %	
ADL/CEA	0.0	0.0	1368	27	Hagerty et al, 1977
ADL/CEA	0.5	0.0	1262	31	
ADL/CEA	0.75	0.0	1216	33	
Pennsylvania (FMC)	1	0.0	1120	42	Krizek, 1979

(CV12)

TABLE 4-4

SHEAR STRENGTH CHARACTERISTICS OF STABILIZED LDA SLUDGE

SOURCE OF SAMPLES	FLY ASH TO FILTER CAKE RATIO	LIME %	OTHER ADDITIVES	TRIAXIAL COMPRESSION		UNCONFINED COMPRESSION	REFERENCE
				C' KN/m^2	ϕ' DEGREE	KN/m^2	
Illinois (FMC)	1	-	-	20	30^o-35^o	30-300	Krizek, 1979
ADL/CEA	0.33	5+	-	-	-	186	Hagerty et al, 1977
	0.33	15+	-	-	-	269	
	1	5+	-	-	-	131	
	1	15+	-	-	-	386	
	1	0	2% Cement+	-	-	609	Hagerty et al, 1977
	1	0	2% Cement+	-	-	1470	
	1	0	2% Cement++	-	-	1138.5	
	1	0	2% Cement++	-	-	1138.5	

(CV12)

\+ Curing time is 14 days

++ Curing time is 28 days

TABLE 4-5

UNCONFINED COMPRESSION TEST ON STABILIZED LDA SLUDGE

SOURCE OF SAMPLE	FLY ASH TO FILTER CAKE	LIME CaO %	SOIL	CEMENT %	MOISTURE CONTENT %	CURING TIME DAYS	Qu KN/m^2	REFERENCE
ADL/CEA	0	0	0	0	35	14	103.5	Hagerty et al, 1977
	0	0	0	0	32	14	69	
	0.33	5	0	0	36	14	186.3	
	0.33	14.2	0	0	28	14	269.1	
	1	5	0	0	18	14	131	
	1	15	0	0	16	14	386	
	1	0	0	2	16	14	669.4	
	1	0	0	2	16	28	1470.0	
	1	0	0	2	26	28	1138.5	
	1	0	0	2	17	28	1683.5	

(CV13)

TABLE 4-6

COEFFICIENT OF PERMEABILITY OF STABILIZED LDA SLUDGE

SOURCE OF SAMPLE	FLY ASH TO FILTER CAKE RATIO	SOLID CONTENT %	PERMEABILITY cm/sec	REFERENCE
ADL/CEA	-	70.0	5.6×10^{-5}	Hargerty et al, 1977
	-	76.7	2.9×10^{-4}	
	-	71.2	2.2×10^{-4}	
ADL/ Pilot Plant	-	72.0	2.1×10^{-5}	Hagerty et al, 1977
Pennsylvania (FMC)	-	-	$10^{-5} - 10^{-6}$	Krizek, 1979
Illinois (FMC)	1	-	$1 \times 10^{-5} - 10^{-6}$	Krizek, 1979
GPC Scholz	0.3	-	4.8×10^{-5} - 8.3×10^{-5}	Rossoff et al, 1979

(CV12)

TABLE 4-7

COMPRESSION INDICES OF STABILIZED LDA SLUDGE

SOURCE OF SAMPLE	MOISTURE CONTENT %	STRESS RANGE KN/m^2	COMPRESSION INDICE	REFERENCE
ADL/CEA	86	24 - 48	0.02	Hagerty et al, 1977
		96 - 240	0.06	
		480 - 960	0.10	
Pennsylvania	-	-	0.75	Krizek, 1979

(CV12)

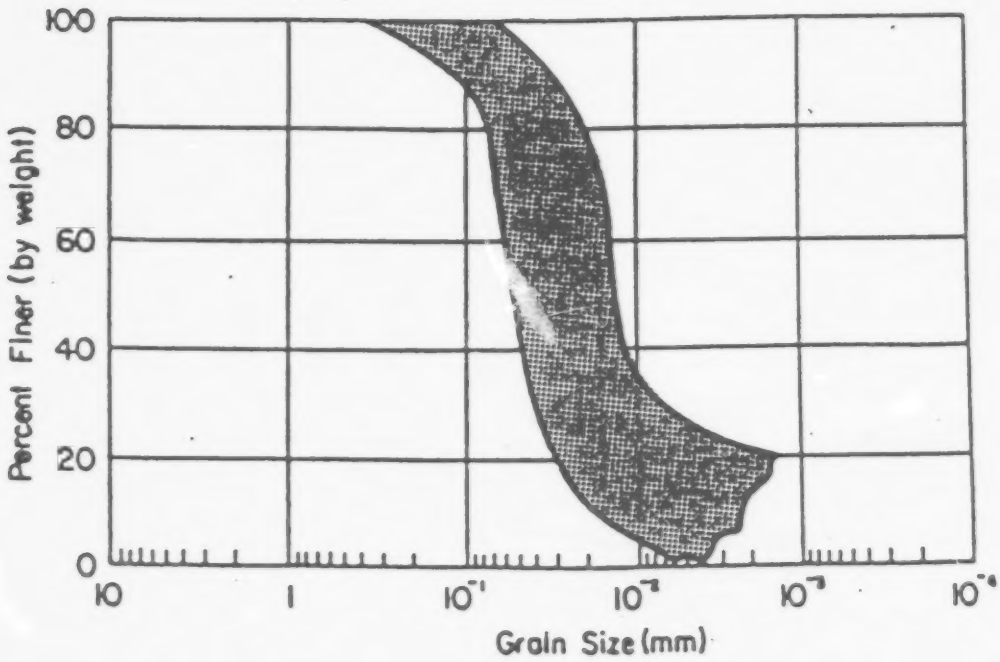

FIGURE 4-1

PARTICLE SIZE DISTRIBUTION OF DOUBLE ALKALI SLUDGES
(KRIZEK ET AL, 1987)

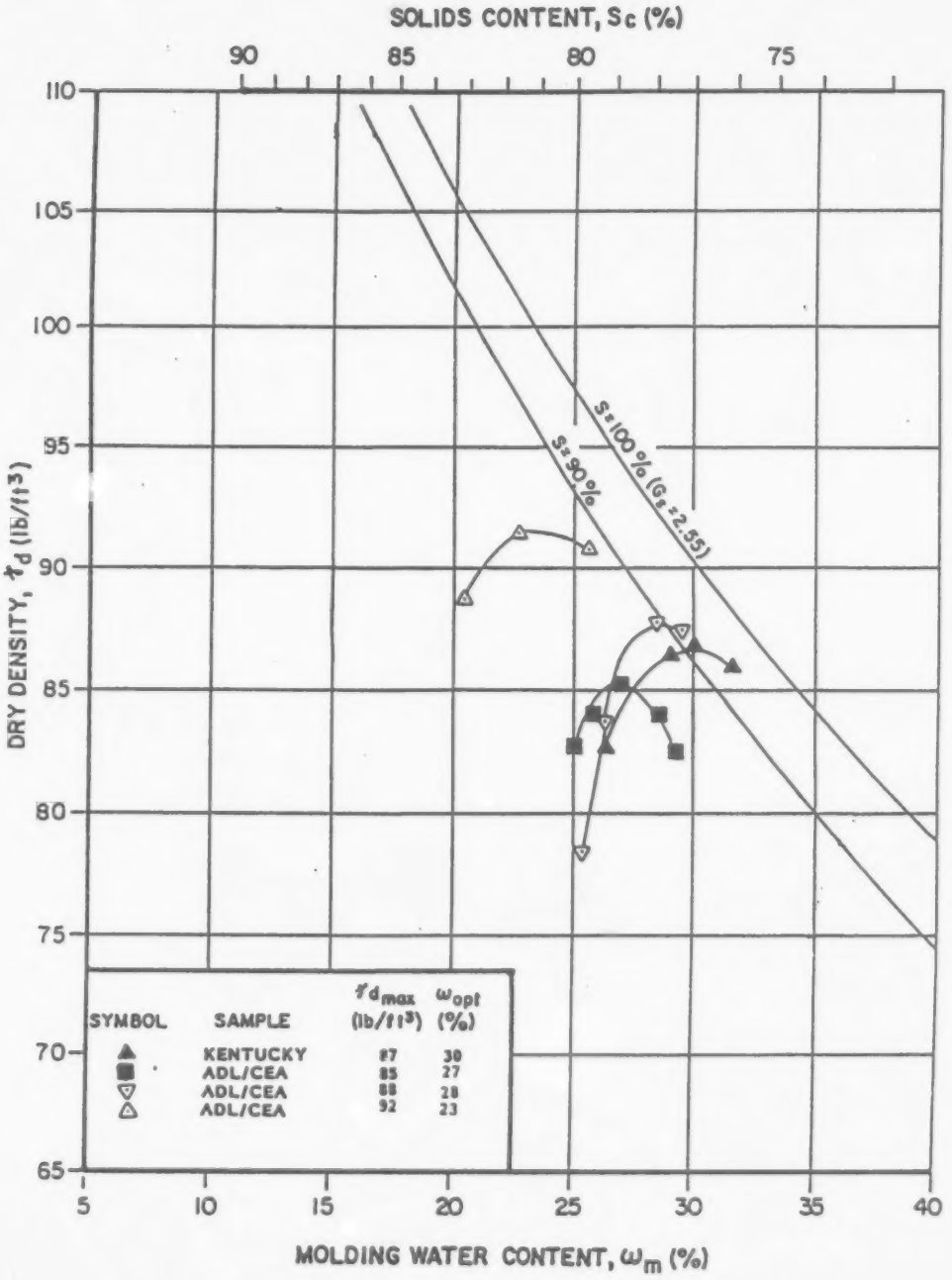

FIGURE 4-2

COMPACTION CHARACTERISTICS OF LDA SLUDGES
(HAGERTY & ULLRICH, 1980)

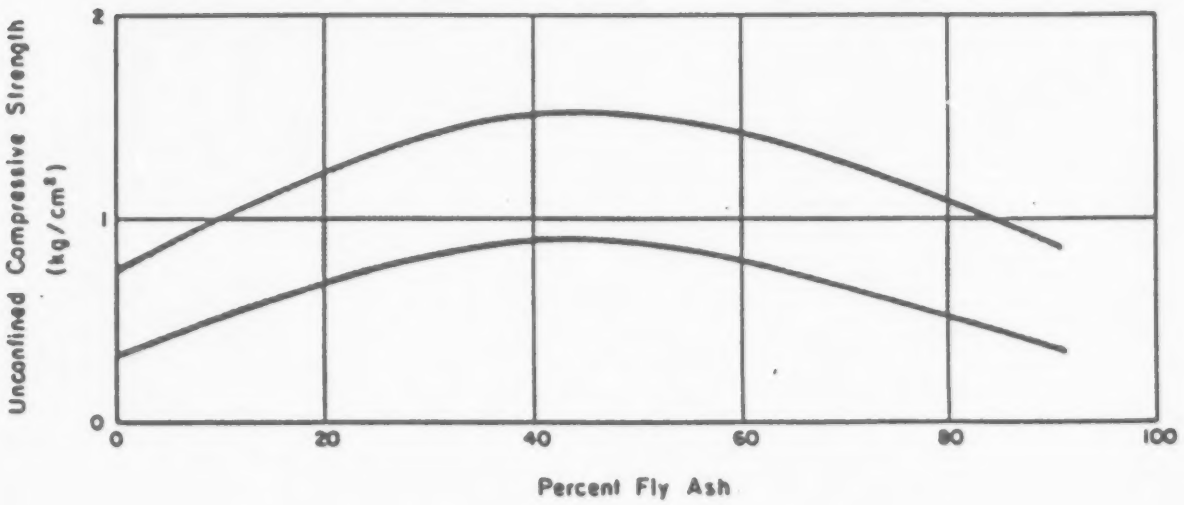

FIGURE 4-3
EFFECT OF FLY ASH ON UNCONFINED COMPRESSIVE STRENGTH OF LDA SLUDGES
(KRIZEK ET AL, 1987)

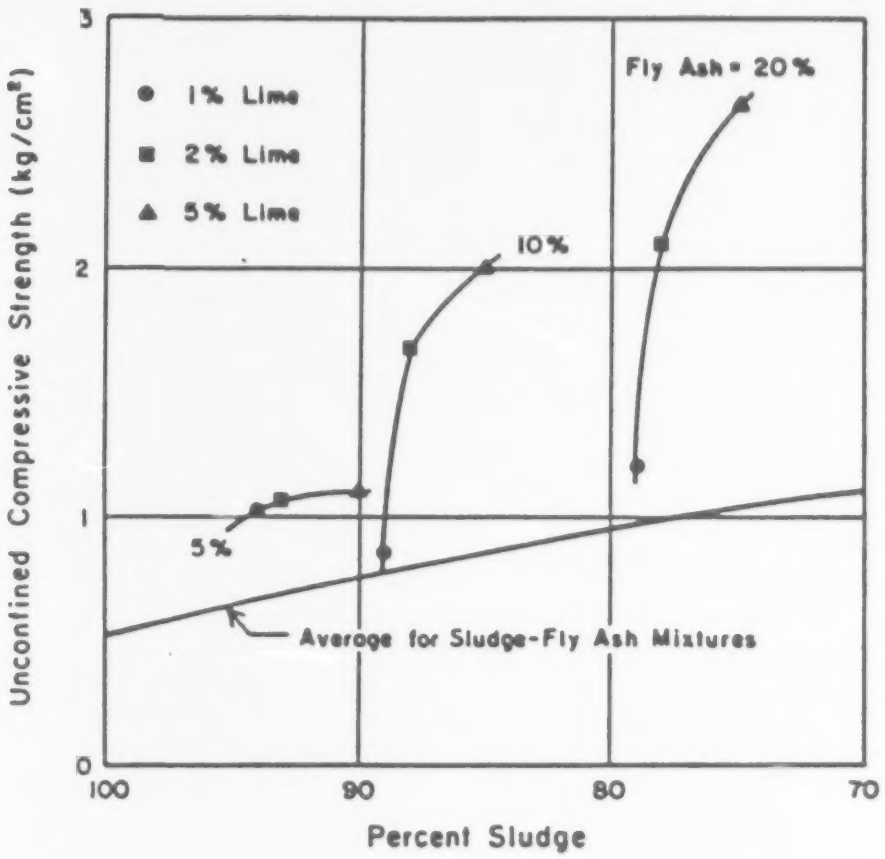

FIGURE 4-4
EFFECT OF LIME ON UNCONFINED COMPRESSIVE STRENGTH
OF LDA SLUDGE-FLY ASH MIXTURES
(KRIZEK ET AL, 1987)

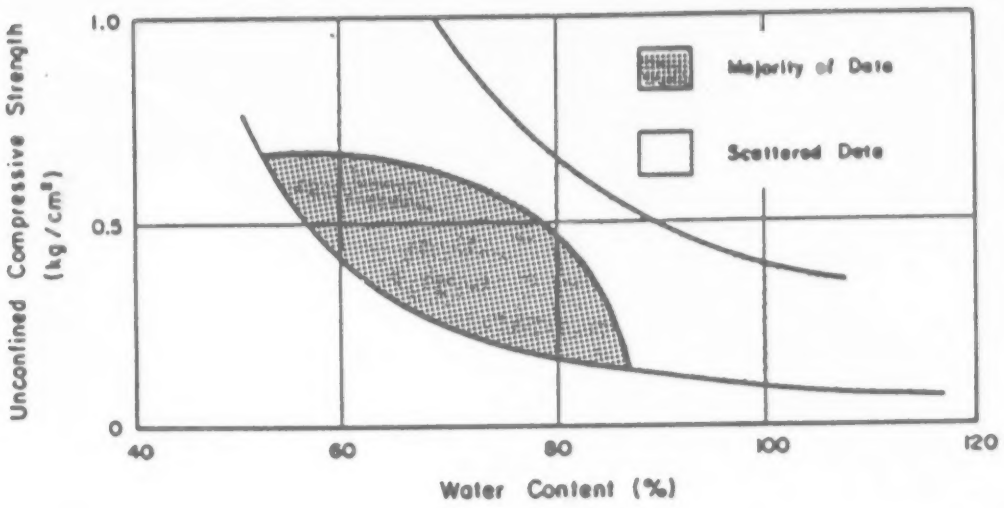

FIGURE 4-5
UNCONFINED COMPRESSIVE STRENGTH OF LDA SLUDGES
(KRIZEK ET AL, 1987)

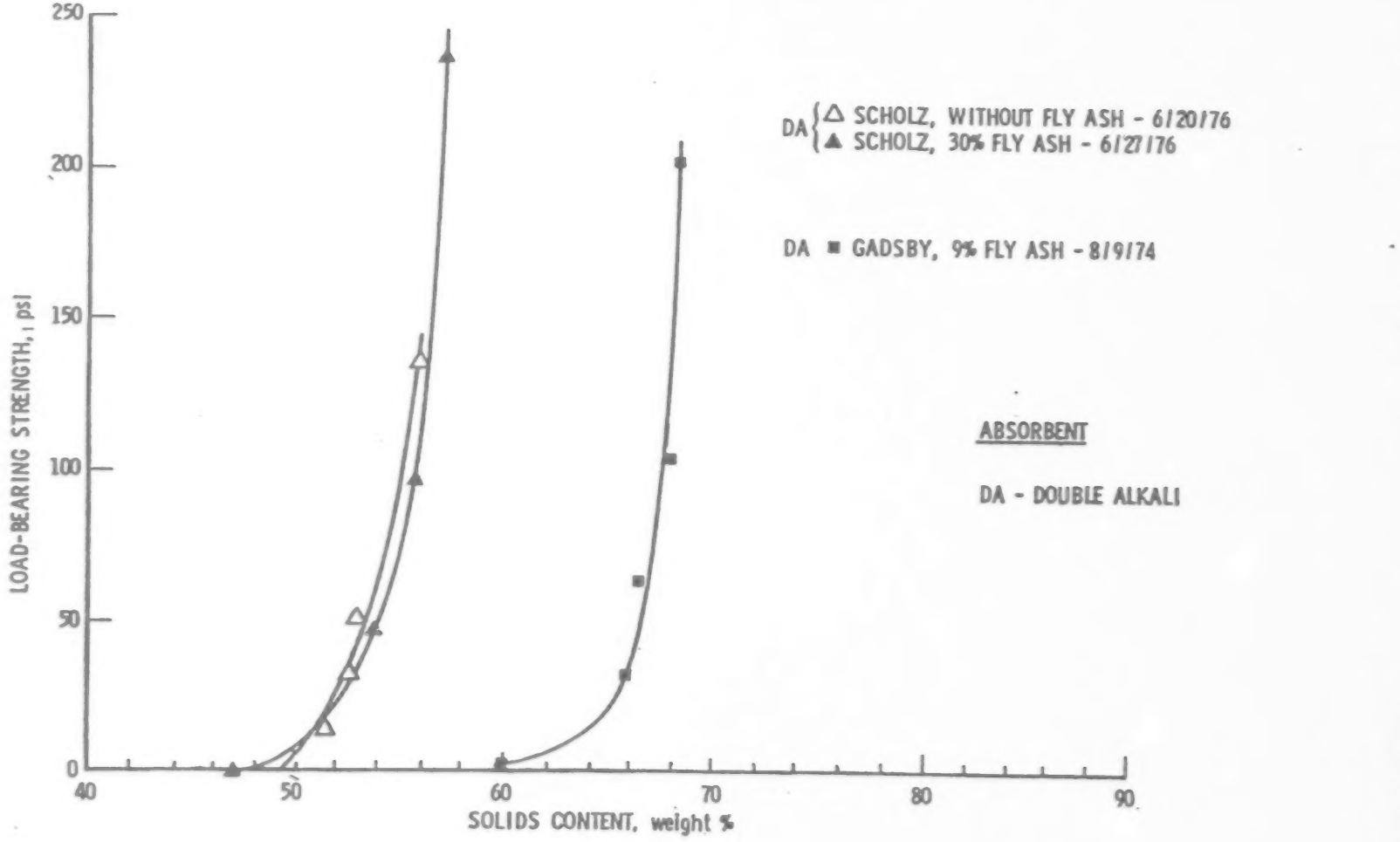

FIGURE 4-6

LOAD-BEARING STRENGTH OF LDA SLUDGE AS A FUNCTION OF MOISTURE, FLY ASH, AND SLUDGE ORIGIN (ROSSOFF ET AL, 1979)

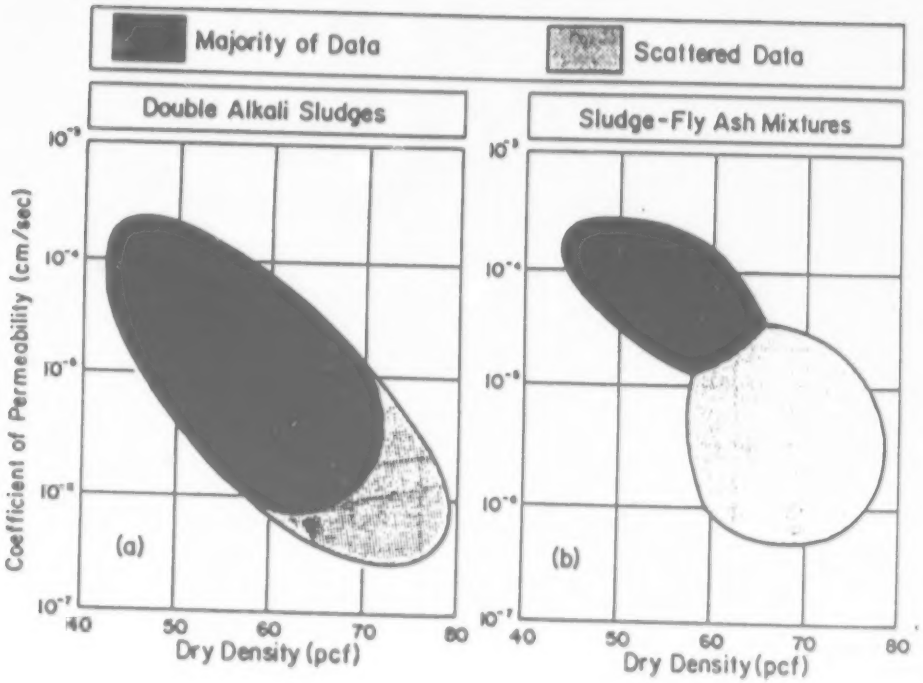

FIGURE 4-7

PERMEABILITY OF LDA SLUDGES AND
SLUDGE-FLY ASH MIXTURES
(KRIZEK ET AL, 1987)

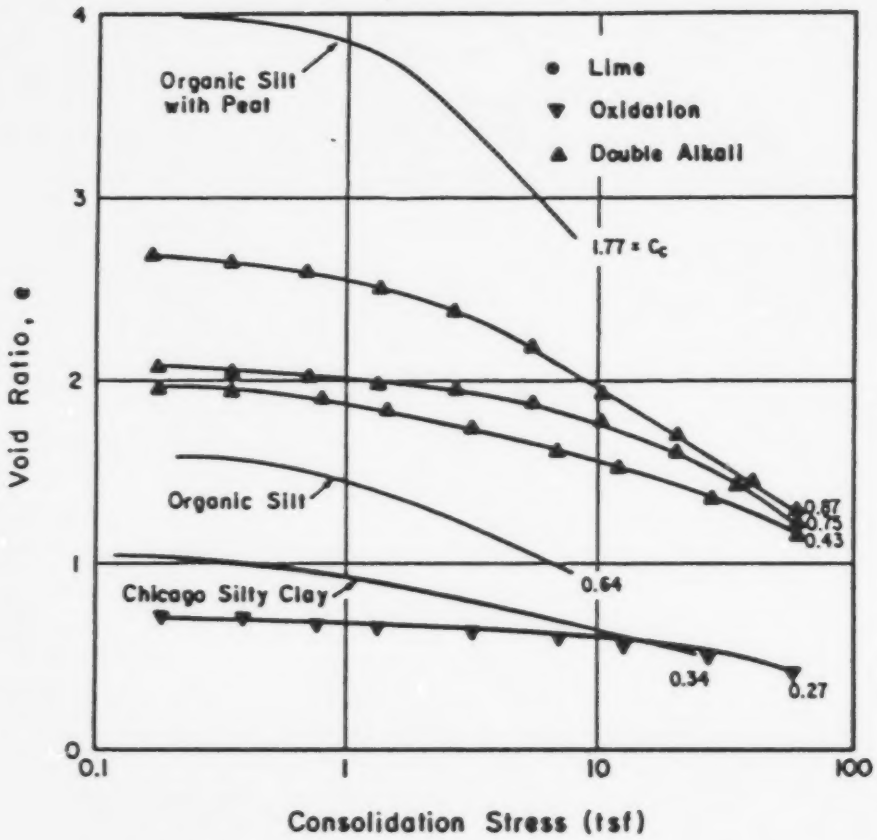

FIGURE 4-8

CONSOLIDATION CURVES FOR LDA SLUDGES
(KRIZEK ET AL, 1987)

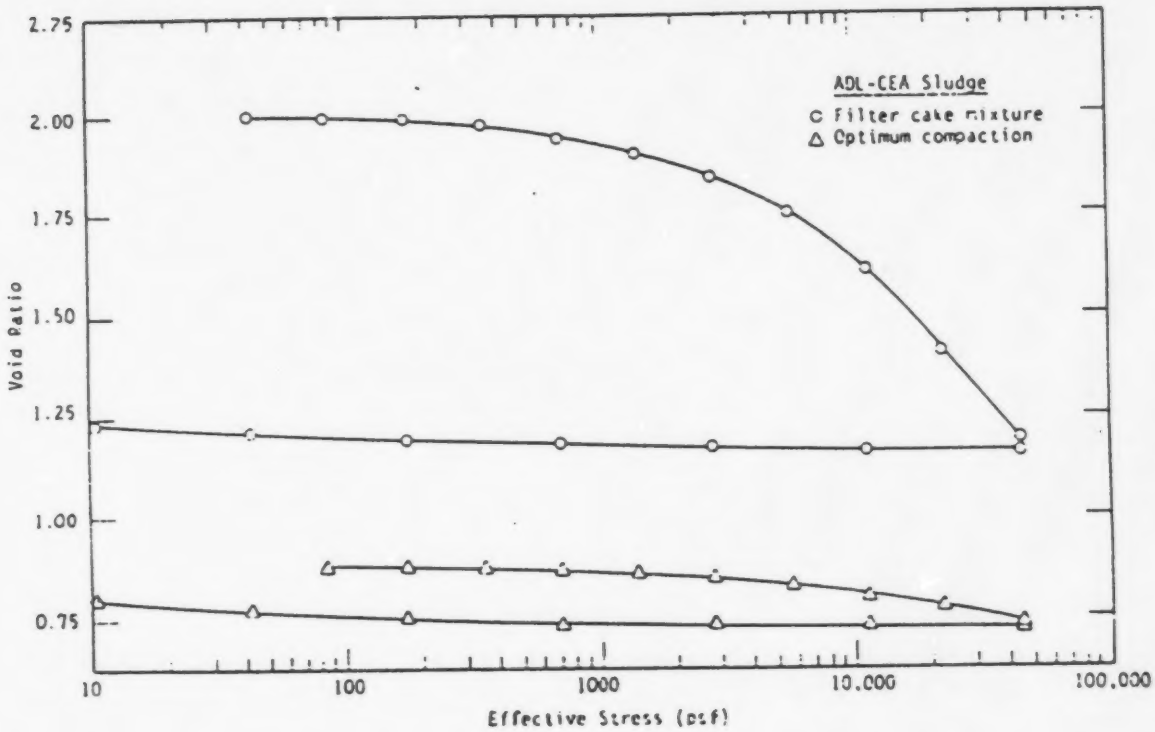

FIGURE 4-9

CONSOLIDATION CURVES OF LDA SLUDGE
(HAGERTY ET AL, 1977)

5.0 ENGINEERING CHARACTERISTICS OF STABILIZED LIMESTONE WET SCRUBBER SLUDGE/FILTER CAKE

5.1 General

Klym and Dodd, (1974) reported a study conducted on a LSWS sludge obtained from Ontario Hydro's research laboratory. The study included index properties, compaction characteristics, shear strength characteristics, permeability and the ability of cemented sludges to resist softening under severe moisture conditions.

Garlanger et al, (1983) investigated the engineering properties of a LSWS gypsum-fly ash waste produced at the Widows Creek Steam Plant in Stevenson, Alabama. Operation experience and geotechnical laboratory testing were performed on the sludge to evaluate the feasibility of disposing the sludge by wet stacking.

Hagerty et al, (1977) investigated the engineering characteristics of six FGD sludges which included a wet limestone scrubber sludge from a plant in the Midwest.

Rossoff et al, (1979) summarized the engineering characteristics of FGD sludges from various processes.

5.2 Physical Properties of Treated LSWS Sludge

5.2.1 Mineralogy and Composition

Hagerty et al, (1977) pointed out that in limestone scrubbing systems, the calcium salts produced might consist of as little as 20% calcium sulfite with the remainder being hydrated calcium sulfate. Unreacted limestone might account for 5% - 30% of the sludge produced, which also usually included 15% - 50% fly ash.

Garlanger et al, (1983) reported that the TVA LSWS sludge was composed of 41% calcium sulfate, 0.7% sulfite, 43% fly ash and 13% unreacted limestone. The crystalline phases detected from X-ray diffraction analyses were gypsum, magnetite, hematite, calcite, dolomite and quartz.

5.2.2 Index Properties

5.2.2.1 Particle Size Distribution

The particle size distribution of the TVA LSWS sludge is presented in Figure 5-1, which indicates that an average of 76% by dry weight of the particles are finer than 74 μm. Most of the particles above 74 μm were unreacted limestone whereas the sulfate and sulfite crystals and fly ash were smaller than 74 μm.

The particle size distribution of the Ontario Hydro sludge mixed with fly ash is presented in Figure 5-2.

5.2.2.2 Specific Gravity

The specific gravity of the TVA LSWS sludge was determined to vary from 2.34 to 2.93 which are in general agreement with a specific gravity of 2.46 reported for a waste with 25% calcium sulfate and 75% fly ash.

5.2.2.3 Water and Solids Content

Klym and Dodd, (1974) pointed out that in order to produce a stable landfill, the sludge would have to be dewatered to at least 70%. The addition of dry solids to the sludge can help bring the water content down to an acceptable value for proper compaction of the sludge to take place. The difference in the consistency of untreated and treated sludges are clearly demonstrated in Figure 5-3.

5.2.3 Compaction Characteristics

Klym and Dodd, (1974) reported the results of compaction tests performed on limestone wet scrubber sludge generated from Ontario Hydro's Lakeview G.S. plant. The results of the compactibility study on the treated mixture are summarized in Table 5-1.

The study indicated that a LSWS sludge can only be conveniently handled, transported and effectively compacted into stable landfill if it is dewatered to a solids content of 77% or above.

The mixture which exhibited 'ideal' compaction properties were firm and moist after compaction. The mixtures which fall within this group were the samples with 65% fly ash and 15% of quicklime, 39% fly ash and 5% quicklime, and 65% fly ash with either 5% or 15% cement.

The overall test results show that the addition of additives to first dewater and then solidify the sludge appears feasible.

The use of fly ash to filter cake ratio of one alone yielded a mix which was readily compactable, however, there appeared to be no cementing action developed and it was possible that such a compacted mix could soften if inunated (Klym and Dodd, 1974). A further addition of small quantity of either lime or cement had resulted in a mixture which could readily be compactable and its strength could increase gradually with time. The fly ash acts as a filler, increasing the final solids content of the mix, thus yielding a compactable mix at a lower lime or cement content.

Hagerty et al, (1977) reported that the optimum moisture content and the corresponding maximum dry density on the Midwest LSWS sludge mixed with fly ash were 33% and 1237 kg/m^3.

Coltharp et al, (1979) reported the results of compaction tests for sludge and sludge and fly ash mixtures on a naturally oxidized limestone sludge and a forced oxidation limestone sludge as shown in Table 5-2.

5.2.4 Shear Strength Characteristics

5.2.4.1 Triaxial Compression Test

The results of the unconsolidated undrained triaxial compression tests described in Klym and Dodd, (1974) are shown in Figure 5-4. For the sample with 1:1 fly ash to filter cake (i.e. 65% fly ash to 65% filter cake) ratio, the effective stress parameters, c' and Ø' were 0.6 kg/cm^2 (8.5 psi) and 32°, respectively. With the addition of 5% cement to the sample with 0.6:1 fly ash to filter cake ratio, there was a slight decrease in c' to 0.35 kg/cm^2 (5.0 psi) but a significant increase in Ø' to 42°.

Garlanger et al, (1983) investigated the relationship between dry density and the internal friction angle of compacted sludge and the results are presented in Figure 5-5.

Consolidated undrained triaxial tests on sludge mixtures containing low alkali ash are given in Table 5-3 (Coltharp et al, 1979).

5.2.4.2 Unconfined Compression Test

The unconfined compression test results described in Klym and Dodd, (1974) are presented in Figures 5-6 through 5-9 and summarized in Table 5-4.

With the addition of fly ash alone, the unconfined compression strength of the sludge mix resembled that of a stiff clay which ranged from 1.06 kg/cm^2 (15 psi) to 1.76 kg/cm^2 (25 psi). There appears to be no noticeable gain in strength with time which indicates that there was no cementing action between sludge and fly ash (Figure 5-6).

A significant increase in strength was observed when 5% of cement was added to the mix even after a delay of compaction of 1 day as shown in Figure 4-7. Increasing the cement content to 10% resulted in little extra gain in strength.

Addition of fly ash with either cement or quicklime exhibited appreciable strength gain (Figures 5-8 & 5-9), particularly when the cement content was 15% as shown in Figure 5-8. The strength gain generally increased with time.

It was pointed out by Klym and Dodd, (1974) that with about 2 weeks of moist curing, the specimens which were too dry due to a high quicklime or fly ash content took on a very dry appearance and significant 'alligator cracking' was observed. Specimens which were tested in this condition yielded very low compressive strength.

Seale, (1979) reported the results of an unconfined compression test on two LSWS sludges mixed with fly ash. Sludge (1) contained 60% fly ash, 5% $CaCo_3$, 30% $CaSo_3$ and 7% $CaSo_4$ and sludge (2) contained 15% fly ash, 22% $CaCo_3$, 50% $CaSo_3$ and 13% $CaSo_4$. The results are presented in Table 5-5. It is noted that the unconfined compression strength increased with time and the high fly ash content sludge generally produced stronger fixed material.

Coltharp et al, (1979) reported the results of adding fly ash on the unconfined compression strength of LSWS sludges. The results of tests on sludges mixed with a low alkali ash and 3% to 5% of quicklime are shown in Table 5-6 and the results of sludges mixed with a high alkali ash alone are presented in Table 5-7. All samples were cured in a humid atmosphere at 72°F for 30 days. The samples mixed with a high-alkali ash showed a higher compressive strength than those with a low-alkali ash.

5.2.4.3 Load Bearing Test

Rossoff et al, (1979) reported the results of load bearing strength of a number of FGD sludges. The procedures of testing were summarized in the previous section. The results of the tests are presented in Figure 5-10.

The LSWS sludge from APS Cholla had to be dewatered to the highest solids content of all sludges tested before it developed significant strength. In general, all sludges showed negligible strength at solids content of less than 76%.

5.2.5 Permeability

Since LSWS sludge contains a fair amount of sulfate crystals and sulfate-rich sludges are usually more permeable than sulfite-rich sludges (Hagerty et al, 1977), therefore, LSWS sludge is expected to be more permeable than other FGD sludges.

Klym and Dodd, (1974) reported that the coefficient of permeability of a densely compacted, untreated sludge from Ontario Hydro had a value of 9.0×10^{-6} cm/sec which is equivalent to that of sand clay. The addition of either fly ash or cement resulted in a slight reduction in permeability. A further reduction in permeability was experienced when mixtures of both fly ash with cement and fly ash with lime were used as shown in Table 5-8.

Klym and Dodd, (1974) pointed out that any pollutants in the sludge and fly ash mixtures might become physically bound within the cemented material, thus attenuating the amount of potential pollutants from entering the environment.

From the permeability measured, it can be seen that the permeability of these sludges in the field would not be less than 1×10^{-5} cm/sec unless a costly amount of cementing fixative was added to the sludge during landfilling.

Garlanger et al, (1983) reported that the coefficient of permeability is insensitive to void ratio and varies within the range of 5×10^{-5} to 5×10^{-4} cm/sec as shown in Figure 5-11.

5.2.6 Compressibility and Consolidation Characteristics

Garlanger et al, (1983) investigated the compressibility and consolidation characteristics of TVA LSWS sludge which is mainly composed of calcium sulfate (41%) and fly ash (43%). The void ratio versus effective consolidation pressure is presented in Figure 5-12. The compression ratio is approximately 0.05 between consolidation pressures of 0.01 to 1.0 kg/cm^2.

The sludge consolidated rapidly and was followed by a secondary consolidation which resulted in a slight increase in the dry density in time at a given effective stress (Garlanger et al, 1983).

The coefficient of consolidation, cv, of the TVA sludge was estimated to be in the range of 0.01 to 0.10 cm^2/sec. The coefficient of secondary compression was to vary from 0.09% to 0.23% with an overall average of 0.15% (Garlanger et al, 1983).

CHAPTER 5

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TABLE 5-1

MIX CONSISTENCIES WITH VARIOUS ADDITIVES
FOR LAKEVIEW GS SCRUBBER LSWS SLUDGE WITH 65% SOLIDS

(Klym and Dodd 1974)

MIX PROPORTIONS	CONSISTENCY OF MIX	REMARKS ON COMPACTABILITY
Sludge + 50% Lime Sludge + 10% Lime Sludge + 5% Cement Sludge + 10% Cement	Soft and Wet	Both lime mixes were too wet to compact, even after 1 week of retention. The cement mixes were too wet to compact initially, but compactable after 24 hours.
Sludge + 15% Cement Sludge + 52% Fly Ash Sludge + 39% Fly Ash + 5% Cement Sludge + 39% Fly Ash + 15% Cement	Firm and Wet	All mixes slightly too wet causing some slumping of specimens after removal from mold.
Sludge + 65% Fly Ash Sludge + 15% Lime Sludge + 39% Fly Ash + 5% Lime Sludge + 65% Fly Ash + 5% Cement Sludge + 65% Fly Ash + 15% Cement	Firm and Moist	Ideal mix combinations for compaction.
Sludge + 65% Fly Ash + 5% Lime	Firm and Dry	Slightly drier than above mixes but compactable.
Sludge + 39% Fly Ash + 15% Lime Sludge + 65% Fly Ash + 15% Lime	Powdery and Dry	Too dry and powdery for proper compaction.

(CV13)

TABLE 5-2

RESULTS OF COMPACTION TEST FOR
LSWS SLUDGES AND SLUDGE/FLY ASH MIXTURES

(Coltharp et al, 1979)

	SLUDGE/ASH RATIO	MOISTURE CONTENT %	COMPACTED DENSITY Kg/m^3
Naturally Oxidized Limestone	1:0	35.4	1317
	1:2	19.6	1549
Forced Oxidation Limestone	1:0	30.5	1412
	1:2	19.5	1543
Naturally Oxidized Limestone	1:0	40.6	1174
	1:2	22.0	1476

(CV12)

TABLE 5-3

CONSOLIDATED UNDRAINED TRIAXIAL
TESTS OF LSWS SLUDGE/LOW ALKALI ASH MIXTURES

(Coltharp et al, 1979)

	NATURALLY OXIDIZED LIMESTONE		FORCED OXIDIZED LIMESTONE		NATURALLY OXIDIZED LIME	
Solids Content	48%		70%		45%	
Prior to Ash Addition Ratio CaO to Scrubber Solids	0.03		0.03		0.05	
Sludge Ash Ratio	Cohesion Kg/cm^2	Friction Angle (Deg)	Cohesion Kg/cm^2	Friction Angle (Deg)	Cohesion Kg/cm^2	Friction Angle (Deg)
1 : 0	1.13	24	0.92	23	0	0
1 : 0.5	0.14	39	1.55	40	0.07	37
1 : 1.0	0.21	13	0.21	50	0.92	28
1 : 2.0	0	55	0.07	42	0.63	38

(CV12)

TABLE 5-4

SHEAR STRENGTH CHARACTERISTICS OF STABILIZED LIMESTONE SCRUBBING SLUDGE

SOURCE OF SAMPLE	FLY ASH TO FILTER RATIO	LIME CONTENT	ADDITIVE CONTENT	SOLID CONTENT	WATER CONTENT	UNCONFINED COMPRESSION STRENGTH Kg/cm^2 CURING TIME DAYS					REFERENCE
						0	7	14	28	AS NOTED IN PARENTHESES	
		%	%	%	%						
Ontario Hydro	0	0	0	74.6	34	1.55	-	-	-	-	Klym and Dodd 1974
	0	0	50 (soil)	78.1	28	1.48	-	-	-	1.13 (30)	
	0	0	66 (soil)	82.0	22	1.20	-	-	-	1.69 (30)	
	0	0	80 (soil)	84.7	18	1.83	-	-	-	3.66 (29)	
	0.25	0	0	76.3	31	-	-	-	-	7.96 (54)	
	0.25	0	44 (soil)	82.6	21	1.27	-	-	-	4.37 (23)	
	0.25	0	62 (soil)	84.0	19	2.54	-	-	-	5.14 (21)	
	0.25	0	76 (soil)	84.7	18	1.27	-	-	-	6.76 (9)	
	1	0	0	77.5	29	1.62	-	-	-	8.31 (42)	
	2	0	0	84.7	18	0.99	-	-	21.42		
	0	0	6.5(cement)	66.7	50	-	1.13	2.40	4.37	-	
	0	0	13 (cement)	68.0	47	-	1.90	3.10	4.93	-	
	0.6	0	4.2(cement)	75.8	32	-	2.04	7.05	6.55	-	
	0.6	0	12 (cement)	76.9	30	-	18.11	24.16	57.35	-	
	0.8	0	0	76.9	30	-	0.7	1.34	1.34	-	
	1	0	0	78.7	27	-	2.04	1.41	1.62	-	
	1	0	3.4(cement)	79.4	26	-	8.03	11.06	11.06	-	
	1	0	10 (cement)	80.6	24	-	17.05	33.25	45.10	-	
	0.6	4.2	-	75.8	32	-	4.51	7.82	12.61	-	
	1	3.4	-	79.4	26	-	5.00	6.55	5.00	-	

(CV13)

TABLE 5-5

SLUDGE STABILIZATION TESTS

(Seale 1979)

TEST NO.	COMPOSITION (DRY WEIGHT % BASIS)						COMPRESSIVE STRENGTH (PSI) (CURED AT ROOM TEMPERATURE AND 100% HUMIDITY)		
	SLUDGE 1	SLUDGE 2	CaS	CaO	FBCR	ASH	5 DAYS	8 DAYS	11 DAYS
1	100	-	-	-	-	-	< 10	< 10	< 10
2	60	-	-	-	-	40	10	< 10	10
3	50	-	-	-	-	50	< 10	< 10	10
4	90	-	-	10	-	-	60	70	190
5	90	-	10	-	-	-	140	150	180
6	90	-	5	5	-	-	170	200	480
7	80	-	10	10	-	-	320	390	420
8	75	-	-	-	25	-	60	60	100
9	50	-	-	-	50	-	70	80	120
10	25	-	-	-	75	-	250	340	520
11	10	-	-	-	90	-	300	350	600
12	-	100	-	-	-	-	< 10	< 10	< 10
13	-	60	-	-	-	40	< 10	< 10	< 10
14	-	50	-	-	-	50	< 10	10	< 10
15	-	90	5	5	-	-	120	150	220
16	-	80	10	10	-	-	180	190	230
17	-	75	-	-	25	-	50	60	60
18	-	50	-	-	50	-	50	100	120
19	-	25	-	-	75	-	200	220	240
20	-	10	-	-	90	-	220	250	300

(CV13)

TABLE 5-6

UNCONFINED COMPRESSIVE STRENGTH
(Kg/Cm^2) OF LSWS SLUDGE/LOW ALKALI ASH MIXTURES

(Coltharp et al, 1979)

	NATURALLY OXIDIZED LIMESTONE	FORCED OXIDIZED LIMESTONE	NATURALLY OXIDIZED LIMESTONE
Solids Content Prior to Ash Addition	48%	70%	45%
Ratio CaO Scrubber Solids	0.03	0.03	0.05
Sludge-Ash Ratio			
1 : 0	0.27	2.37	0
1 : 0.5	0.66	7.19	3.12*
1 : 1.0	0.85	7.23	7.98*
1 : 2.0	1.20	1.11	4.15

(CV12)

* 60-day cure

TABLE 5-7

UNCONFINED COMPRESSIVE STRENGTH
(Kg/Cm^2) OF LSWS SLUDGE/HIGH ALKALI ASH MIXTURES

(Coltharp et al, 1979)

	NATURALLY OXIDIZED LIMESTONE	FORCED OXIDIZED LIMESTONE	NATURALLY OXIDIZED LIMESTONE
Solids Content Prior to Ash Addition	48%	70%	45%
Sludge-Ash Ratio			
1 : 0.5	4.02	33.31	1.20
1 : 1.0	7.76	51.21	11.49
1 : 2.0	48.05	12.47	42.42

(CV12)

TABLE 5-8

COEFFICIENTS OF PERMEABILITY OF STABILIZED LSWS SLUDGE

(Hagerty et al, 1977 & Coltharp et al, 1979)

SOURCE OF SAMPLE	FLY ASH TO FILTER CAKE RATIO	LIME CONTENT %	CEMENT CONTENT %	SOLID CONTENT %	COEFFICIENT OF PERMEABILITY cm/sec
Ontario Hydro	0	0	0	77	9×10^{-6}
	0	0	5	66	7.6×10^{-6}
	1	0	0	79	7.2×10^{-6}
	0.5	0	5	75	4×10^{-6}
	0.5	0	5	0	5.6×10^{-6}
Shawnee TVA	0	0	0	55	2.5×10^{-4}
	0	0	0	67	6×10^{-5}
Eastern*	-	-	-	-	1×10^{-5}
	-	-	-	-	3×10^{-6}
Western*	-	-	-	-	1×10^{-4}
	-	-	-	-	4×10^{-8}

(CV12)

* Treated by proprietary process (Coltharp et al, 1979)

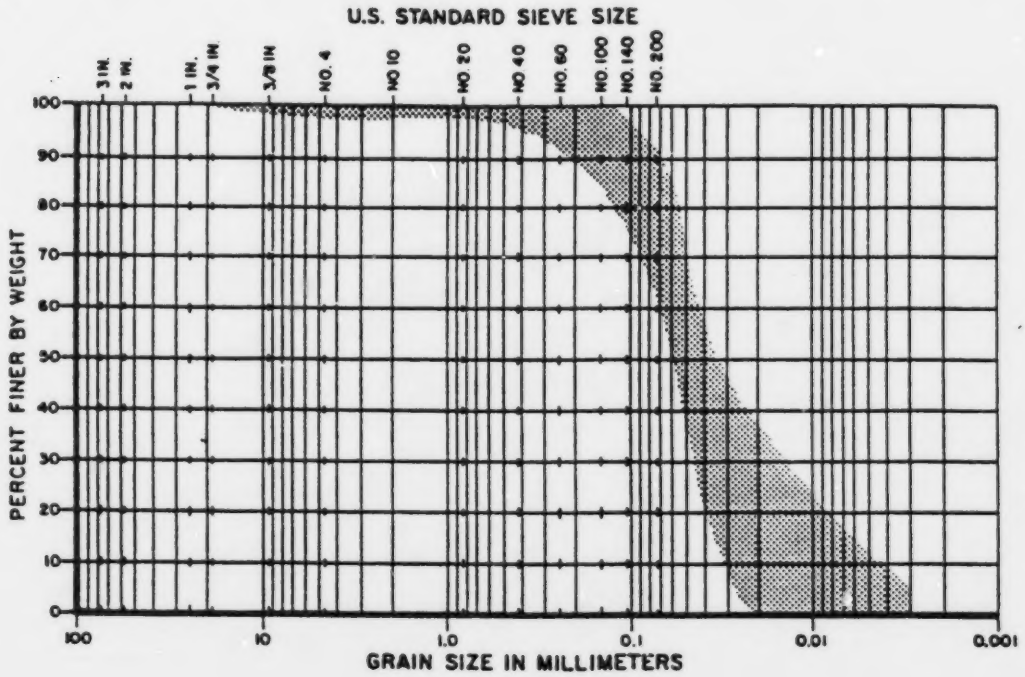

FIGURE 5-1
PARTICLE SIZE DISTRIBUTION OF LSWS SLUDGE
(GARLANGER ET AL, 1983)

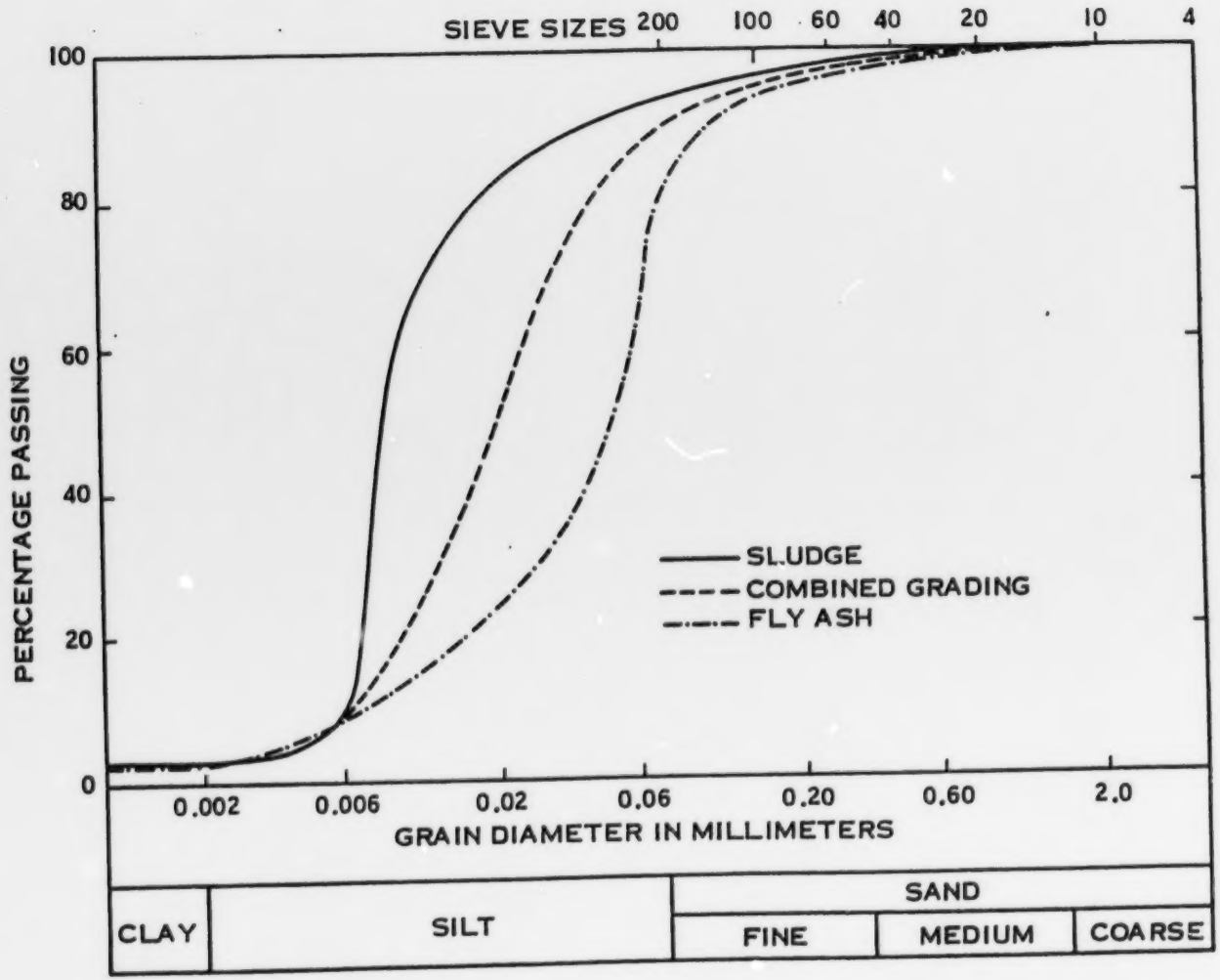

FIGURE 5-2

PARTICLE SIZE DISTRIBUTION CURVES
FOR UNTREATED LSWS SLUDGE AND FLY ASH
(KLYM AND DODD, 1974)

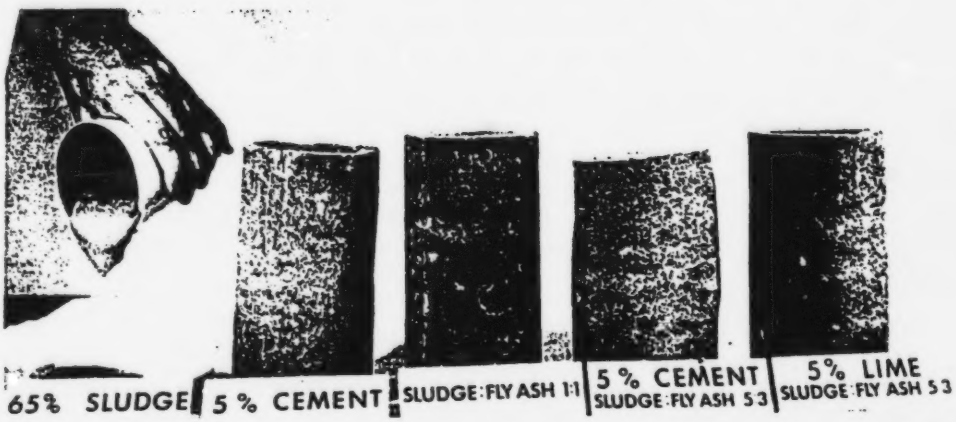

FIGURE 5-3

CONSISTENCY OF 65% SOLIDS SLUDGE AND CONDITION OF LSWS SPECIMENS OF VARIOUS MIXTURES AFTER MOLDING (KLYM AND DODD, 1974)

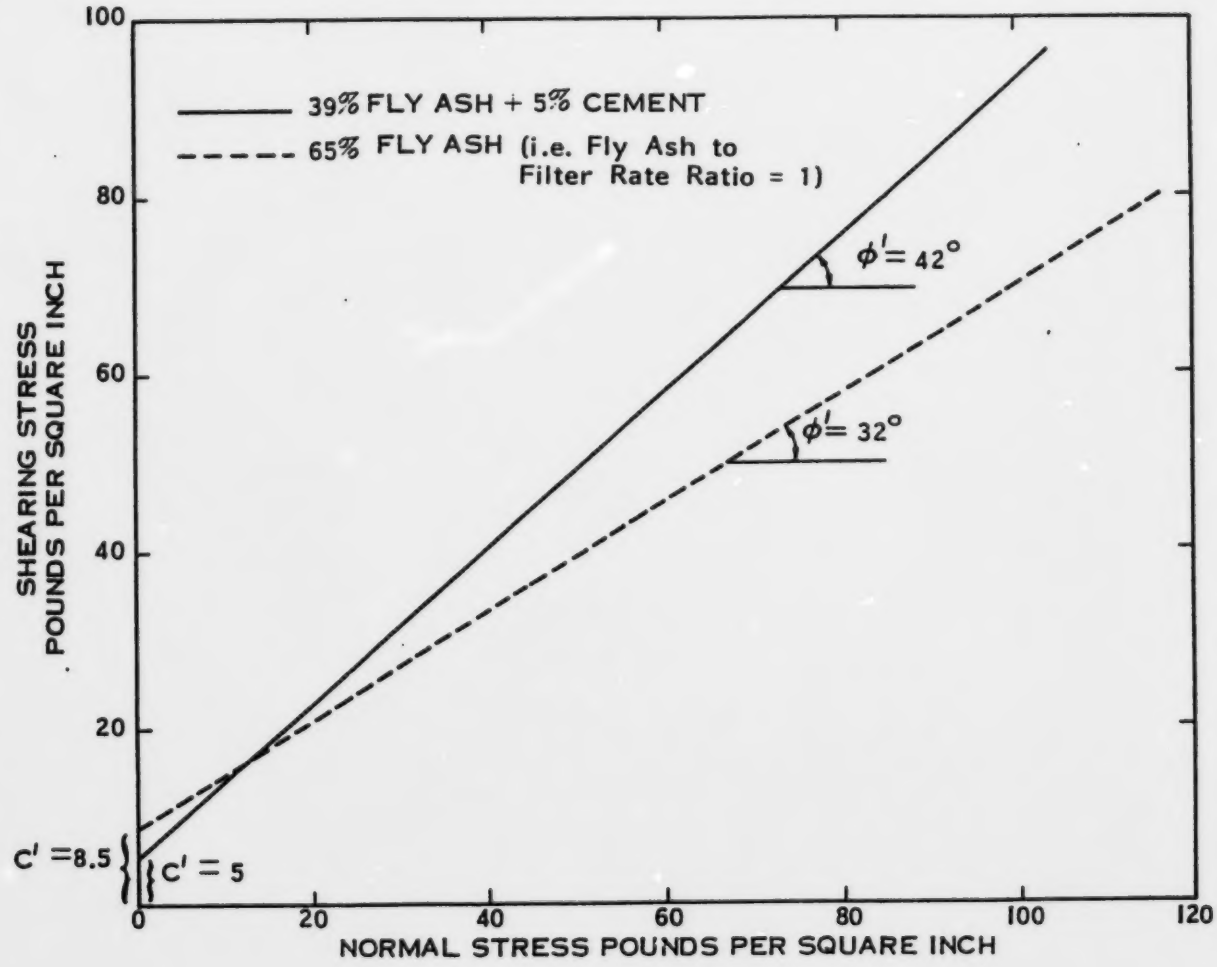

FIGURE 5-4

EFFECTIVE STRESS PARAMETERS FOR TREATED LSWS SLUDGE SPECIMENS FROM A CONSOLIDATED UNDRAINED TRIAXIAL COMPRESSION TEST (KLYM AND DODD, 1974)

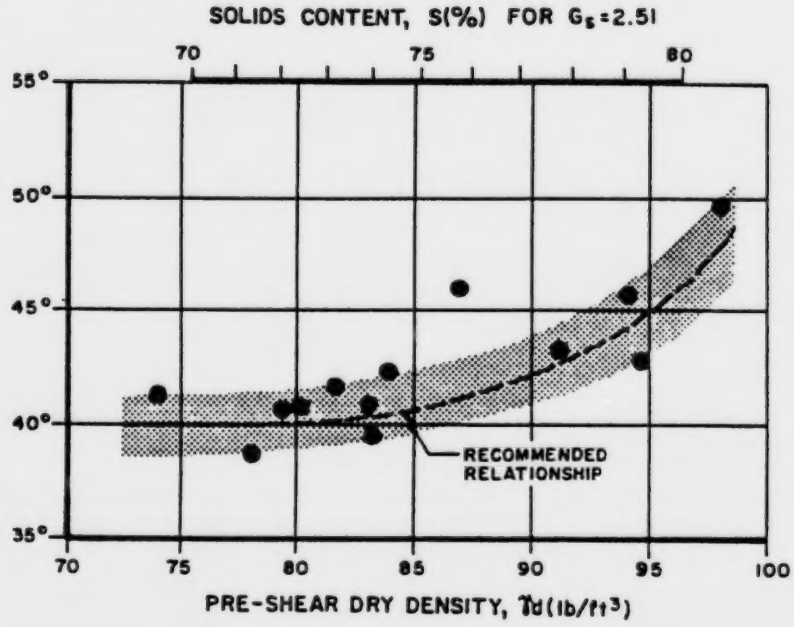

FIGURE 5-5

DRY DENSITY VERSUS ANGLE OF INTERNAL FRICTION OF LSWS SLUDGE (GARLANGER ET AL, 1983)

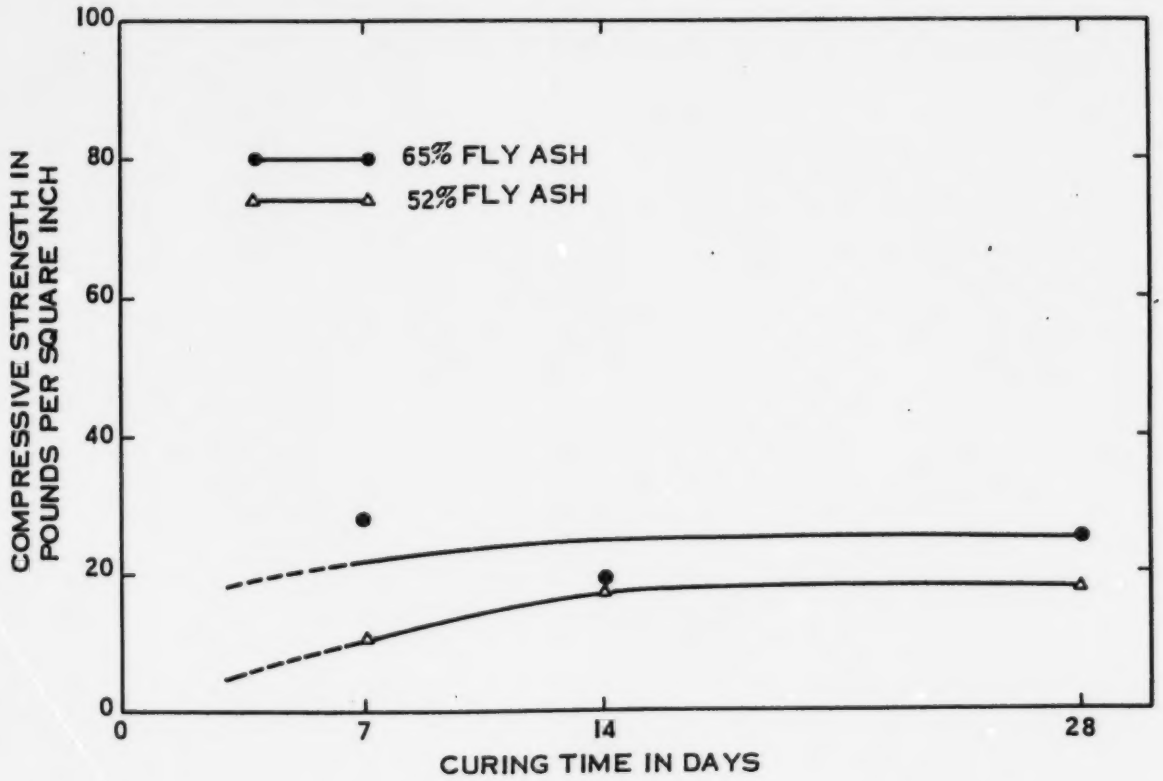

FIGURE 5-6

RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND CURING TIME FOR LSWS SLUDGE TREATED WITH FLY ASH (KLYM AND DODD, 1974)

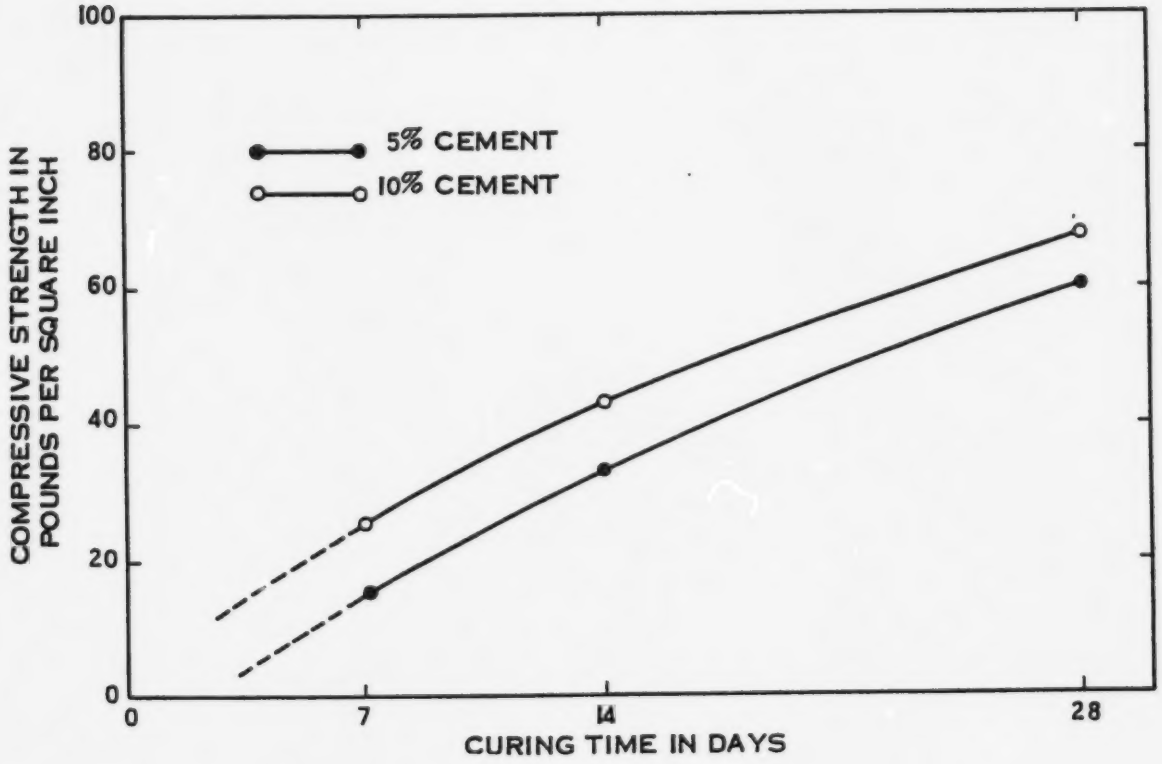

FIGURE 5-7

RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND CURING TIME FOR LSWS SLUDGE TREATED WITH CEMENT (KLYM AND DODD, 1974)

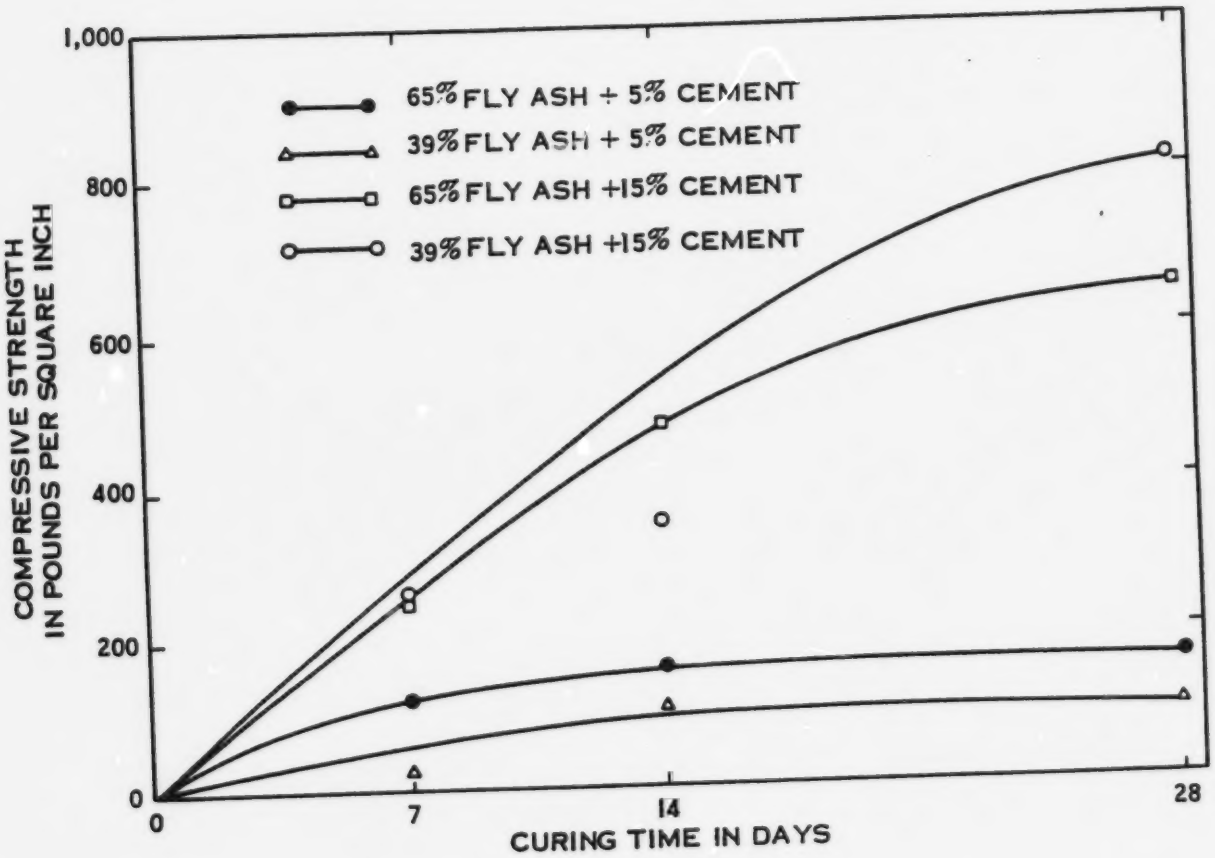

FIGURE 5-8
RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND
CURING TIME FOR LSWS SLUDGE TREATED WITH FLY ASH AND CEMENT
(KLYM AND DODD, 1974)

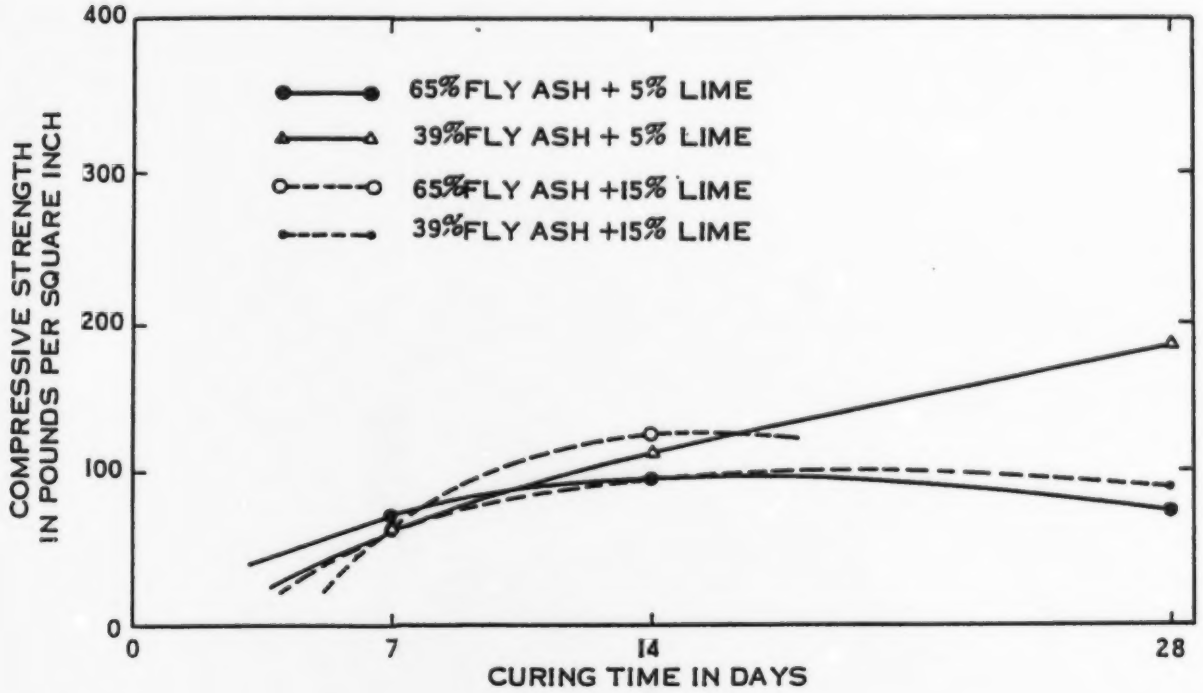

FIGURE 5-9

RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND CURING TIME FOR LSWS SLUDGE TREATED WITH FLY ASH AND QUICKLIME (KLYM AND DODD, 1974)

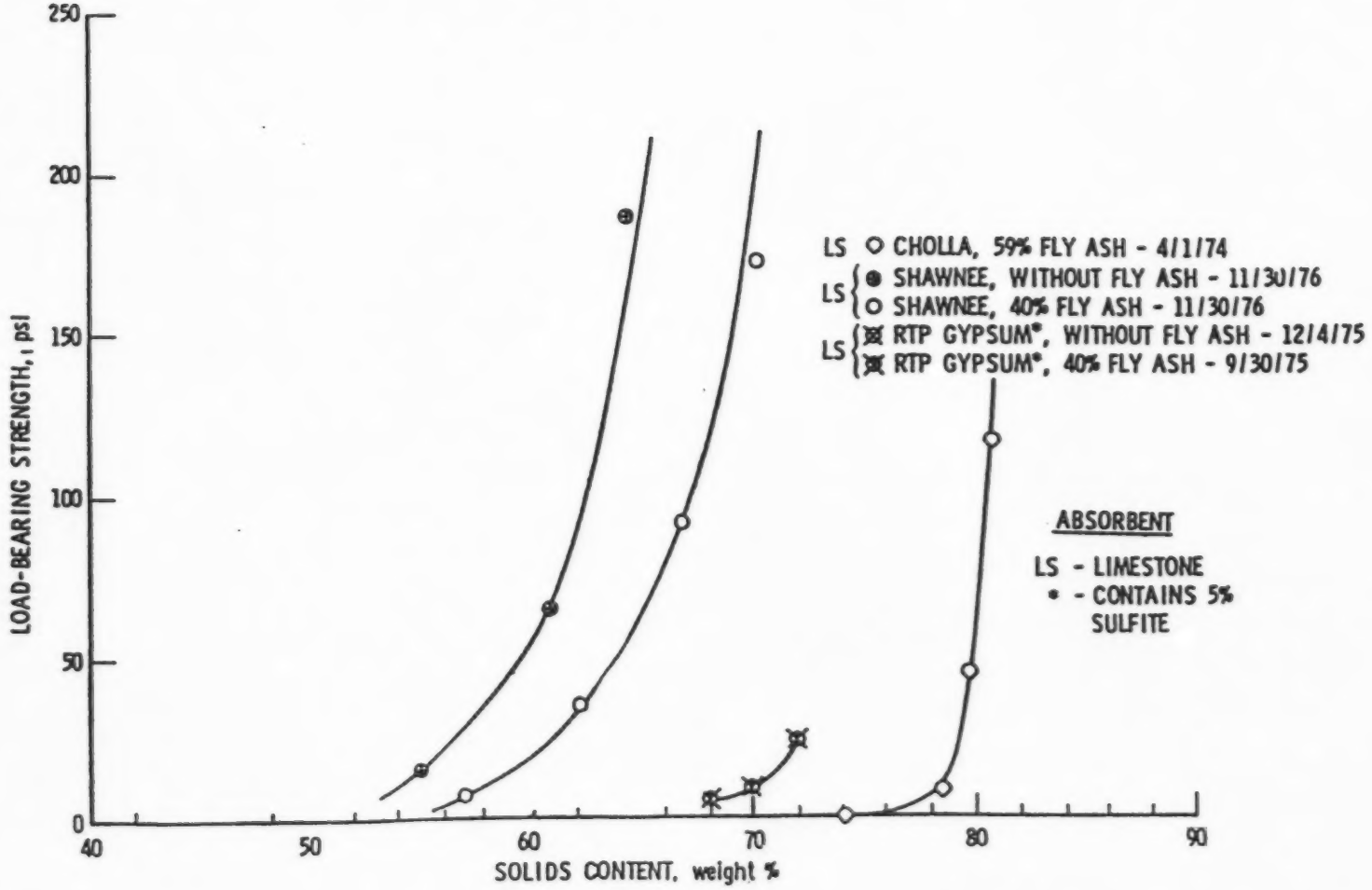

FIGURE 5-10

LOAD-BEARING STRENGTH OF LSWS SLUDGES AS A FUNCTION OF SOLIDS CONTENT
(ROSSOFF ET AL, 1979)

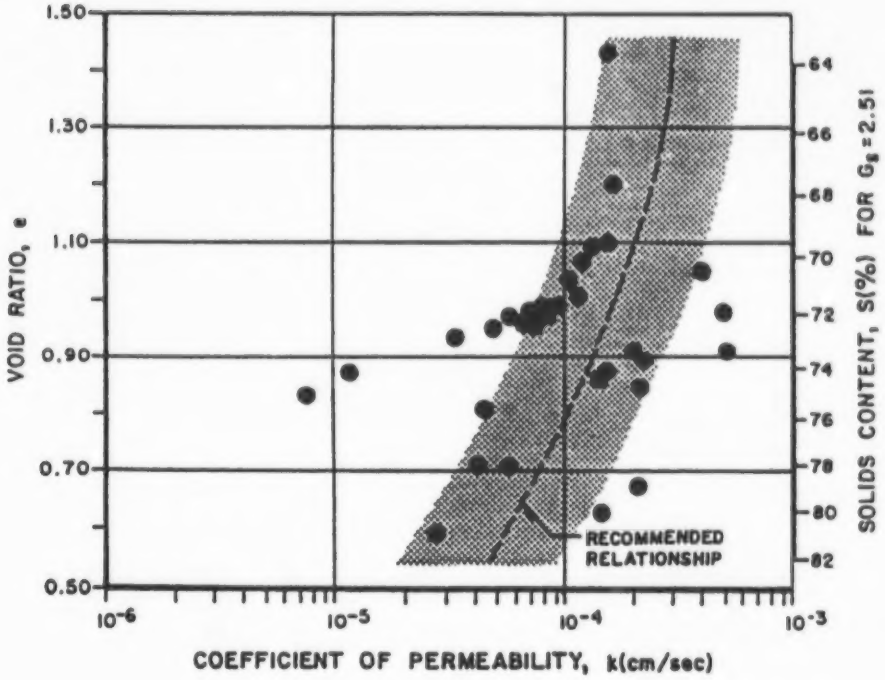

FIGURE 5-11

VOID RATIO VERSUS COEFFICIENT OF PERMEABILITY
OF LSWS SLUDGE
(GARLANGER ET AL, 1983)

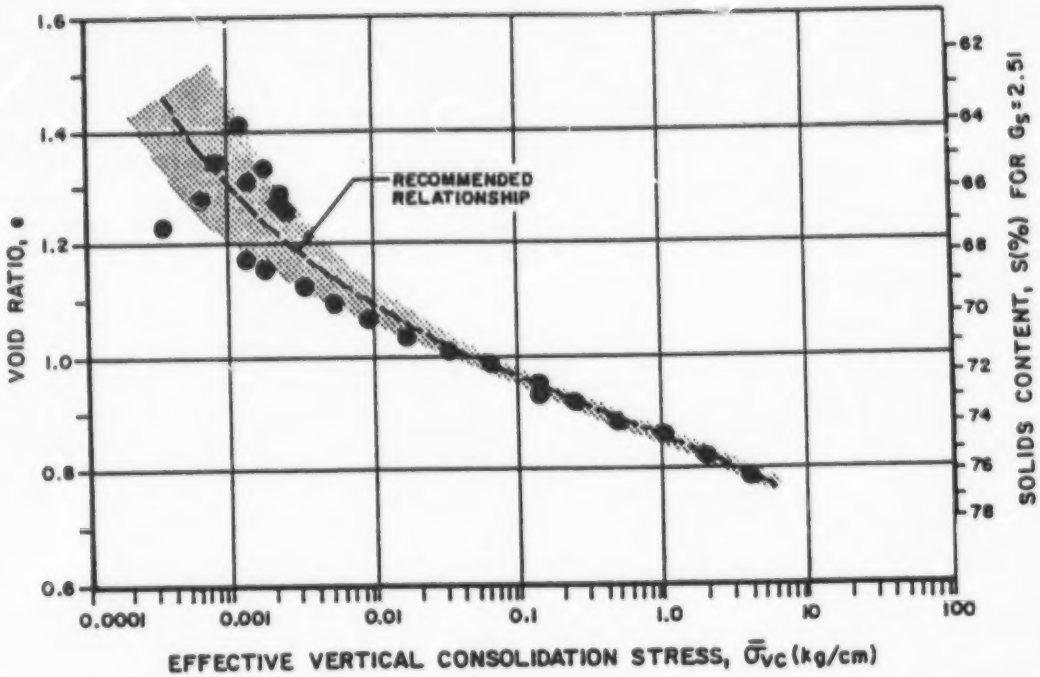

FIGURE 5-12

VOID RATIO VERSUS EFFECTIVE STRESS COMPRESSIBILITY CURVE OF LSWS SLUDGE (GARLANGER ET AL, 1983)

6.0 CHEMICAL COMPOSITION AND LEACHATE ANALYSIS OF FGD SLUDGES GENERATED FROM LSDA, LDA AND LWS PROCESSES

6.1 General

Leachate from FGD sludge disposal areas is an important consideration because of the potential for contaminating surrounding surface or groundwater. The standards used for leachate evaluation were the levels which had been proposed for defining leachates from hazardous water under the Canadian and US standards as given in Table 6-1.

FGD sludges are mainly composed of sulfite and sulfate crystals, lime or limestone.

Leachate composition is difficult to predict because it depends on a variety of factors including pH level at which reaction is taking place, the type of sorbent, stoichiometry of the process, the quality of the coal and the extent of oxidation. The leachate quantity is also difficult to predict and depends on the permeability of the sludge and the underlying solid, hydrology and the groundwater conditions of the site and the specific site design and management practice (such as use of liners and stabilization).

6.2 Chemical Composition and Leachate Analysis of LSDA Sludge

Fox et al, (1982) pointed out that, in general, major constituents of FGD sludge leachates (calcium, chloride, potassium, sodium, sulfite, sulfate, and total dissolved solids) tend to exceed EPA's drinking water standards; whereas trace element concentrations might or might not pose potential surface or groundwater problems. The chemical compositions of an LSDA sludge from Scholz plant are presented in Table 6-2. The EPA's drinking water standards are also given for comparison.

FMC pointed out that double alkali sludges had higher concentration of sodium than other FGD wastes.

Fox et al, (1982) conducted laboratory permeability-leaching tests to determine how stabilization could affect leachate quality. In addition, a field sample of leachate was collected from the disposal area and analyzed for comparison to laboratory mixtures. Leachate samples were analyzed to determine pH, specific conductance, and major constituents (Na, Ca, Cl, Sulfate as So_2, Sulfite So_3 and total solids) and the results are presented in Table 6-3.

The conclusions of the leachate analysis from Fox et al, (1982) are summarized as follows.

1) Stabilization with fly ash without lime fixation had little effect on either peak or steady-state leachate constituent concentration.

2) Fixation with lime could reduce the steady-state leachate concentrations of total solids, sulfate and calcium by around 80% to 85% of the unfixated sludge.

3) The peak concentrations of major constituents within the leachate from fixated samples were only affected slightly.

4) Steady-state leachate concentrations of major constituents were similar for stabilized sludge samples having 1%, 3% and 5% lime. However, additional amounts of lime might be beneficial in minimizing concentrations of metals in the leachate.

5) Peak concentrations of major constituents (chloride, sulfate and dissolved solids) from all samples, treated and untreated, exceeded the limits defined by EPA's drinking water standards.

6) Results from the analyses of laboratory mixtures were compared with those obtained from the field samples. These showed that the laboratory leachate analysis could be extrapolated to estimate the field leachate water quality although the field leachate concentrations were consistently less than the peak laboratory values.

7) Trace element concentrations in field leachate and laboratory mixtures are presented in Table 6-4. Owing to the extraction procedures, the waste would be considered toxic if the indicated leachate concentrations exceeded 100 times the EPA Primary Drinking Water Standards.

6.3 Chemical Composition and Leachate Analysis of LDA Sludge

The sludges generated from the dual alkali process contained higher concentrations of sodium salts than other FGD sludges. Typical constituents of the FMC LDA sludge are presented in Table 6-5.

Rossoff et al, (1979) summarized the leachate analysis on the sludge generated at GPC Plant, Scholz, and the results are presented in Figure 6-1. By comparing the concentration of the constituents in the leachates obtained from plain filter cake and from the filter cake mixed with 30% fly ash, it can be seen that the addition of fly ash did not have a significant effect on the leachate concentration.

Golomb, (1988) investigated the leachate characteristics of sludges obtained from the R.M. Schahfer Station 17 & 18, Indiana and also from Newton Station 1, Illinois by performing the Ontario MOE Leachate Extraction Procedures on the samples. Typical results, as presented in Table 6-6, showed that the wastes were non-"leachate toxic" and were acceptable for landfill in Ontario.

Mulkey, (1983) investigated the removal of heavy metals, suspended carbon and other insoluble compounds from LDA waste. The treatment consisted of precipitating the soluble heavy metal salts with a proprietary product called VSAR chemical and filtering out the flocculants and suspended solids. The advantage of the process is the reduction of environmental liability of future waste site conditions by disposing the treated products as a soil conditioner

for agricultural purpose. Chemical analysis of the treated and untreated sludge showed that there was a significant reduction in heavy-metal concentrations.

6.4 Chemical Composition and Leachate Analysis of LWS Sludge

Van Ness et al, (1979) investigated the potential leachate characteristics of an LWS sludge generated from Paddy's Run Station of Louisville Gas & Electric. The chemical compositions of sludges generated from using a commercial lime and carbide lime as the sorbent are given in Table 6-7. Leachate collected from permeability tests were analyzed. The concentration of major chemical constituents are shown in Table 6-8.

The results of the leachate analysis on Paddy's Run sludge are summarized below.

1) Leachate generation decreased with time. Leachate quality improved with increasing dryness up to an optimum mixture dryness at placement, beyond which the material became brittle and cracked, thereby increasing the permeability and the leachate quantity.

2) The concentration of trace elements found in the collected leachate and soil moisture samples were below RCRA limits.

3) The quality of leachate improved and the quantity decreased with increasing depth beneath the disposal sites. This indicated that the filtering action of the solid might have aided in decreasing the concentration of contaminants reaching the groundwater supply (Mohn et al, 1979).

Rossoff et al, (1979) summarized the leachate analysis on TVA Shawnee Run F for untreated sludge and for sludge mixed with 40% fly ash. The results are presented in Figure 6-2. It appears that the addition of fly ash had no significant change on the concentration of major constituents in the leachate.

CHAPTER 6

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5. Mohn, N.C., Plumley, A.L., Tyler, A.L., and Van Ness, R.P. (1979), "Environmental Effects of FGD Disposal, a Laboratory/Field Landfill Demonstration", EPA Symposium on FGD, Las Vegas, Nevada.

6. Mulkey, M.A., (1983), "Heavy Metals Removal from Double Alkali Waste - Makes Waste Product Usable", EPRI Report No. CS-2897, p. 797-801.

7. Rossoff, J., Rossi, R.C., Graven, W.M., and Leo, P.P. (1979), "Disposal of By-Products from Nonregenerable Flue Gas Desulfurization Systems : Final Report", USEPA Report No. EPA-600/7-79-046, pp. 18-73.

8. Van Ness, R.P., Plumley, A.L., Mohn, N.C., Ullrich, C.R., and Hagerty, D.J., (1979), "Final Report : Pilot Field Studies of FGD Waste Disposal at Louisville Gas and Electric", USEPA Report No. EPA-600/7-81-155.

TABLE 6-1 (GOLOMB, 1988)

ENVIRONMENTAL OBJECTIVES RELATED TO WASTEWATER DISCHARGES IN NORTH AMERICA

	Environment Canada Codes of Practice (1)	Ontario MOE Discharge Criteria (3)	Ontario MOE Surface Water Quality Objectives (16)	Ontario MOE Drinking Water Objectives (17)	US EPA NPDES (3)	US EPA NIPDWS (3,18)	US EPA NSDWR (3)
pH	6.5 - 9.5	5.5 - 9.5	6.5 - 8.5	-	6-9	-	6.5-8.5
Alkalinity	-	-	<1.25 x background	-	-	-	-
SO_4	-	minimize (BAT)	-	500	-	-	(250)
Cl	-	minimize (BAT)	-	250	-	-	(250)
NO_3 (as N)	-	-	-	10.0	-	-	-
Ag	-	-	<0.0001	0.05	-	-	-
Al	-	-	undefined	-	-	-	-
As	-	-	<0.1	0.05	-	0.05	-
B	-	-	undefined	5.0	-	-	-
Be	-	-	<0.11	-	-	-	-
Ba	-	-	undefined	1.0	-	1.0	-
Cd	-	0.001	<0.0002	0.005	-	0.01	-
Cr	0.5	1.0	<0.1	0.05	-	0.05	-
Cr (VI)	0.05	-	-	-	-	-	-
Cu	0.5	1.0	<0.005	1.0	-	-	1.0
Fe	1.0	-	<0.3	0.3	1.0	-	0.3
Hg	-	0.001	<0.0002	0.001	-	0.002	-
F	-	-	-	2.4	-	1.4-2.4	-
Mn	-	-	undefined	0.05	-	-	0.05
Mo	-	-	undefined	-	-	-	-
Ni	0.5	1.0	<0.025	-	-	-	-
Pb	-	1.0	<0.025	0.05	-	0.05	-
Se	-	-	<0.1	0.01	-	0.01	-
Sn	-	1.0	-	-	-	-	-
U	-	-	-	0.02	-	-	-
V	-	-	undefined	-	-	-	-
Zn	0.5	1.0	<0.03	5.0	-	-	5.0
TDS	-	minimize (BAT)	<1.33 x background	500	-	-	(500)
TSS	25	add <15 mg/L	-	-	100	-	-
Oil & Grease	15	15	-	-	20	-	-
Total Residual Chlorine	0.2	-	-	-	-	-	-
Phenols	-	0.02	-	0.002	-	-	-
BOD (5-day)	-	15	-	-	-	-	-

All concentrations given in mg/L
NPDES denotes US EPA National Pollutant Discharge Emission Standards
NIPDW denotes US EPA National Interim Primary Drinking Water Standards
NSDWR denotes US EPA National Secondary Drinking Water Regulations (bracketed figures proposed)
BAT denotes best available technology

TABLE 6-2
CHEMICAL COMPOSITION OF LSDA SLUDGE LIQUORS
(FOX ET AL, 1982)

Parameter	Range for FGD Sludge Liquors*	EPA Interim Primary or Proposed Secondary Drinking Water Standard
pH	2.8 - 12.8	6.5 - 8.5
Specific Conductance, μ mhos/cm	3,000 - 15,000	—
MAJOR CONSTITUENTS (mg/l)		
Calcium, Ca	420 - 3,000†	—
Chloride, Cl	470 - 5,000†	250
Magnesium, Mg	3.0 - 2,750	—
Potassium, K	5.9 - 32	—
Sodium, Na	14.0 - 20,000**	—
Sulfite, SO_3	0.8 - 3,500	—
Sulfate, SO_4	720 - 30,000**	250
Total Dissolved Solids	2,500 - 95,000**	500
TRACE ELEMENTS		
Arsenic, As	< 0.004 - 0.3	0.05
Cadmium, Cd	0.002 - 0.11	0.01
Chromium, Cr	0.001 - 0.5	0.05
Copper, Cu	< 0.002 - 0.6	1.0
Fluoride, F	0.7 - 70	1.4 - 2.4
Iron, Fe	0.02 - 8.1	0.3
Lead, Pb	0.0014 - 0.55	0.05
Manganese, Mn	0.007 - 9.0	0.05
Mercury, Hg	0.0004 - 0.07	0.002
Selenium, Se	0.001 - 2.2	0.01
Silver, Ag	0.005 - 0.6	0.05
Zinc, Zn	0.01 - 27	5.0

*Source: FGD Sludge Disposal Manual, 2nd Editon, EPRI CS-1515, September 1980.

**The highest levels shown reflect single measurements on an unwashed double-alkali filter cake.

†Single values as high as 45,000 mg/l for Ca and 43,000 mg/l for Cl have been measured.

TABLE 6-3

PEAK AND STEADY STATE LEACHATE
CONSTITUENT CONCENTRATIONS FROM LSDA SLUDGE
(FOX ET AL, 1982)

Description	S_c (%)	R	L (%)	pH Peak	pH SS	G (μmhos/cm) Peak	G SS	Sodium, Na (mg/l) Peak	Sodium, Na SS	Calcium, Ca (mg/l) Peak	Calcium, Ca SS	Sulfate SO_4 (mg/l) Peak	Sulfate SO_4 SS	Sulfite, SO_3 (mg/l) Peak	Sulfite, SO_3 SS	Chloride, Cl (mg/l) Peak	Chloride, Cl SS	Total Solids (mg/l) Peak	Total Solids SS
Unstabilized FGD Filter Cake	67.0	0.00	0.0	2.5	7.2	45,000	2,250	28,000	90	750	750	57,000	1,600	1,700	<20	2,290	22	100,000	2,900
Stabilized FGD Sludge Without Lime Fixation	56.0	0.75	0.0	2.5	7.2	50,000	2,180	34,000	40	700	700	69,200	1,500	<20	<20	4,520	18	118,000	2,840
Stabilized FGD Sludge	56.0	0.75	1.0	8.4	7.9	33,500	650	15,000	46	250	120	27,500	150	<100	<100	950	32	46,000	710
Stabilized FGD Sludge	56.0	0.75	3.0	11.8	8.8	48,750	640	30,000	25	155	155	53,000	160	2,200	<20	2,140	15	95,000	425
Stabilized FGD Sludge	56.0	0.75	5.0	11.9	8.9	45,750	600	28,000	23	15	110	49,500	175	<100	<100	5,690	30	88,000	475
Stabilized FGD Sludge	47.0	0.75	3.0	11.4	8.3	44,500	690	24,000	60	140	140	46,000	320	1,400	<20	1,140	15	76,000	620

Where: S_c = Filter Cake Solids Content; R = Fly Ash to Filter Cake Ratio; L = Lime Content; Peak = Peak Leachate Constituent Concentration; and SS = Steady-State Leachate Constituent Concentration.

TABLE 6-4

TRACE ELEMENT ANALYSIS FOR SCHOLZ LEACHATE AND FIELD-WORTHY SAMPLE OF LSDA SLUDGE (FOX ET AL, 1982)

Parameter	Leachate[1]	Field-Worthy Samples[2]	EPA Interim Primary Drinking Water Standard	EPA Secondary Drinking Water Standard
Aluminum	1.5	6.8	-	-
Calcium	130	1155	-	-
Iron	0.13	12.7	-	0.3
Magnesium	5.6	30.0	-	-
Potassium	480	33.3	-	-
Sodium	15,000	735	-	-
Beryllium	<0.01	.010	-	-
Boron	-	2.57	-	-
Silicon	4.6	515	-	-
Cadmium	<.01	0.02	0.01	-
Chromium	<.05	0.10	0.05	-
Copper	<.01	0.08	-	1
Lead	<.05	0.14	0.05	-
Manganese	0.65	0.47	-	0.05
Nickel	<.05	0.22	-	-
Zinc	0.11	0.27	-	5
Arsenic	22[3]	0.04	0.05	-
Selenium	0.63	0.004	0.01	-
Mercury	0.00096	0.014	0.002	-

[1] Leachate collected from Scholz disposal site on 5/29/81.

[2] Scholz laboratory mixture with fly ash-to-filter cake ratio of 1:1, 3% lime addition, and 56% solids content.

[3] The high arsenic value that was measured in the field leachate was not found in any of the stabilized sludge leachate samples from the laboratory testing program.

Source: Leachate analysis performed by Vester J. Thompson, Jr., Inc. field-worthy sample analyzed by Arthur D. Little, Inc., using EPA's extraction procedure (EP).

TABLE 6-5
CHEMICAL ANALYSIS OF FMC LDA SLUDGE (FMC, 1987)

Composition (wt. %)	As Is Cake	Stabilized Cake	Fixated Cake
$CaSO_x$ yH_2O	52.91	38.83	38.00
$CaCO_3$	4.53	3.32	3.25
$NaHSO_3$	0.48	0.35	0.34
Na_2SO_3	0.57	0.42	0.41
Na_2SO_4	1.10	0.81	0.79
NaCl	1.25	0.92	0.90
Inert Dissolved Solids	0.30	0.22	0.21
Inert Suspended Solids	2.56	1.88	2.05
H_2O	36.30	26.64	26.07
Fly ash	0	26.62	26.05
CaO	0	0	1.92
	100.0	100.0	100.0

TABLE 6-6
LEACHATE ANALYSIS OF LDA SLUDGE (SCHAHFER STATION)
(GOLOMB, 1988)

R.M. Schahfer Station 17 & 18, Northern Indiana Public Service Co. - Filter Cake

Parameter	Aerobic		Backfill Use: Max Acceptable Extract Concentration (Monofill Test)/32/	Hazardous Waste Categorization: Max Extract Concentration for Exemption (Co-disposal Test) /33/
	Monofill	Co-Disposal		
pH	11.58	4.88	-	-
Specific Conductivity (mS/m)	-	NA	-	-
As	<0.001	<0.001	0.05	5
Ba	*	*	1.0	100
B	2.29	4.83	5.0	500
Cd	<0.0002	0.0006	0.005	0.5
Cr (total) †	<0.2	<0.2	0.05	5
'WAD' (CN)	<0.04	<0.04	0.2	20
F^-	4.8	4.0	2.4	240
Pb	<0.002	<0.005	0.05	5
Hg	<0.0002	<0.0002	0.001	0.1
NO_3^-(as N)	0.03	0.03	10.0	1000
NO_2^-(as N)	0.015	0.006	1.0	100
Total [NO_3^-+NO_2^-] (as N)	0.05	0.04	10.0	1000
U †	0.03	0.03	0.02	2
PCBs	<0.001	<0.001	0.003	0.3
Se	0.002	0.002	0.01	1
Ag	<0.0005	<0.0005	0.05	5
Cl^-	33	35	1250	-
Cu	<0.1	<0.1	5.0	-
Fe	<0.5	<0.5	1.5	-
Mn	<0.05	0.13	0.25	-
Organic N	0.42	1.73	0.75	-
Phenols	<0.001	*	0.01	-
$SO_4^=$	615	2300	2500	-
TDS	-	NA	2500	-
TOC	-	NA	25	-
Zn	<0.02	0.2	25	-
NH_3	<0.01	0.019	-	-

All concentrations given in mg/L
† Analytical interference due to high background Ca concentrations
* Result could not be obtained due to interferences

TABLE 6-7

CHEMICAL ANALYSIS OF LWS SLUDGES USING COMMERCIAL LIME AND CARBIDE LIME (VAN NESS ET AL, 1979)

Analysis	Commercial Lime Sludge		Carbide Lime Sludge	Fly Ash
	As Rec'd	Mg Added		
CaO	40.53	38.07	30.10	1.71
SO_2 (b)	8.63	5.26	5.43	0.78[a]
SO_3 (c)	36.42	39.20	38.13	--
MgO	0.17	1.87	0.19	0.56
Al_2O_3	0.87		3.48	14.8
Fe_2O_3	1.74		4.03	35.8
SiO_2	4.17		10.8	43.0
Na_2O	0.12		0.19	0.33
K_2O	0.05		0.38	1.16
TiO_2	0.01		0.10	0.62
CO_2	7.3		9.0	0.12
Cl^-	0.22		0.19	0.19
Cu (ppm)	10		130	70
Pb (ppm)	40		80	100
Cd (ppm)	2		3	6
Hg (ppm)	<.03		<.03	.06
As (ppm)	10		3	34
Se (ppm)	1		1	1

Note (a): total sulfur, calculated as SO_3

Note (b): total sulfur less sulfite sulfur, calculated as SO_3

Note (c): sulfite sulfur, calculated as SO_2

TABLE 6-8

LABORATORY LEACHATE ANALYSES OF LWS SLUDGE
(VAN NESS ET AL, 1979)

	Sludge Only 55% Carbide Lime 0:1 Fly Ash to Sludge No Fixative		Mix 7 65% Comm. Lime 1:1 Fly Ash to Sludge 3% P. C.		Mix 10 50% Comm. Lime 1:1 Fly Ash to Sludge No Fixative		Mix 9 50% Comm. Lime 1:1 Fly Ash to Sludge 3% CaO	
Pore Volume# Cont.	1 & 2	5 & 6	1 & 2	5 & 6	1 & 2	5 & 6	1 & 2	5 & 6*
μmhos/cm	6850	2500	2850	2000	2550	575	1800	
pH	7.8	7.5	7.8	7.7	9.2	8.0	9.3	
TDS (ppm)	4100	1500	1700	1200	1400	345	1100	
Cl^- (ppm)	345	<5	10	15	20	<5	15	
$SO_3^=$ (ppm)	30	--	40	--	30	20	230	
Cd (ppm)	0.02	<0.01	0.02	<0.01	0.01	0.01	<0.01	
Cu (ppm)	0.06	0.02	0.02	0.02	<0.02	<0.02	<0.02	
Pb (ppm)	0.2	0.1	0.1	0.1	--	--	<0.1	
Hg (ppm)	0.001	0.002	0.018	0.001	0.002	0.002	0.001	
As (ppm)	0.05	0.01	0.03	0.03	0.007	0.003	0.01	
$SO_4^=$ (ppm)	5390	1960	1580	1470	1320	218	440	
Ca (ppm)	260	300	320	300	650	110	6.7	
Se (ppm)	0.023	0.002	--	0.003	0.010	<0.001	0.008	
Mg (ppm)	--	--	0.18	0.16	0.10	0.04	0.02	

* Due to low permeability of samples, pore volumes 5 & 6 were not available after 60 days of collection.

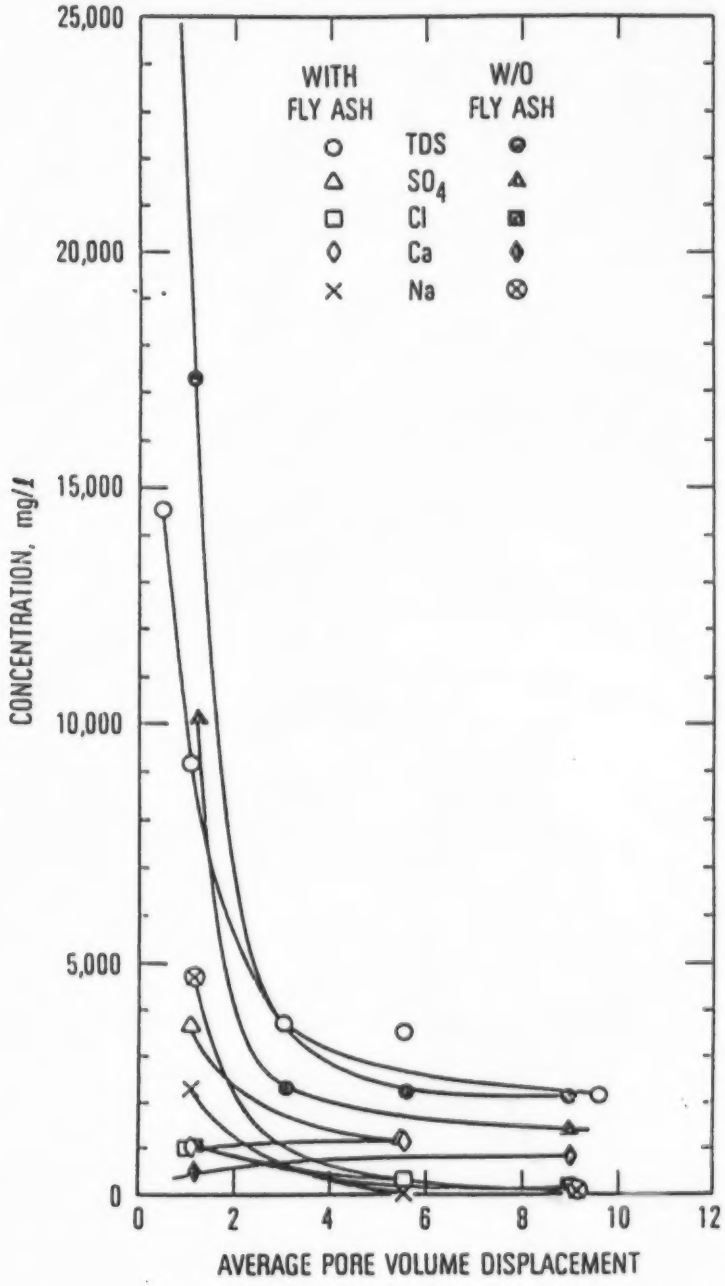

FIGURE 6-1

CONCENTRATION OF MAJOR SPECIES AND TDS IN LEACHATE OF LDA SLUDGE WITH AND WITHOUT FLY ASH: GPC PLANT SCHOLZ (ROSSOFF ET AL, 1979)

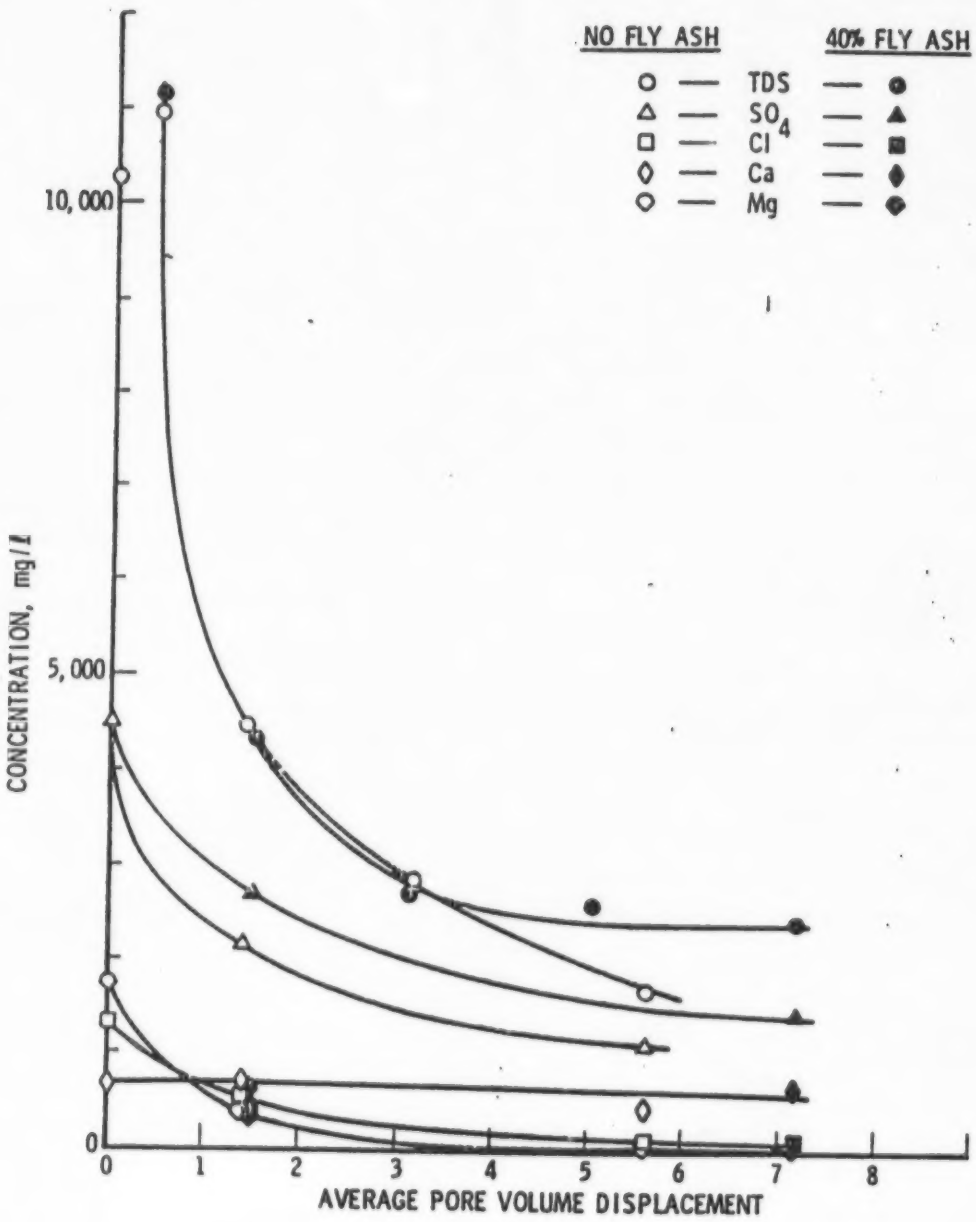

FIGURE 6-2
CONCENTRATION OF MAJOR SPECIES AND TDS IN LEACHATE ANALYSIS OF LWS SLUDGE WITH AND WITHOUT FLY ASH: TVA SHAWNEE, RUN F
(ROSSOFF ET AL, 1979)

7.0 COMMERCIAL FIXATION PROCESS

Several commercial processes are currently available to stabilize FGD wastes. The intent of these fixation processes is to convert utility waste materials to products that can be landfilled in an environmentally acceptable manner and/or to products that can be utilized or marketable. A number of these processes which include the IUCS Poz-O-Tec, Dravo Calcilox, Chemfix and Forced oxidation have been tried with a varying degree of success.

Fixation of the FGD wastes using IUCS Poz-O-Tec, Dravo Calcilox and Chemfix processes are based on mixing cementitious agents such as lime or cement with the waste with or without fly ash. The fly ash increases the solids content of the mixtures while the cementitious agents react with the waste to form a stronger material.

The forced oxidation process converts the sulfite-rich sludge/filter cake to sulfate-rich material which has better engineering properties and therefore is easier to handle for landfilling.

A brief description and applicability of the process, properties of the fixated products and the case histories of some of the common fixation processes are given in the following sections.

7.1 IU Conversion Systems (IUCS) Poz-O-Tec Process

7.1.1 Process Description

The Poz-O-Tec process is a complete waste management system for coal fired power plants (Bacskai and Cleveland, 1979). It encompasses dewatering of the sludge, mixing of the dewatered sludge with fly ash, lime and additives, design and management of the landfill, and placement and compaction of the fixated waste to produce a structurally stable and environmentally acceptable material for land reclamation, roadbase, liners and other useful applications.

The raw materials used are fly ash and lime. In general 10% to 99.5% of fly ash and 2% to 3% of lime are required.

The stabilized waste is a cementitious material as a result of the reactions between the fly ash and the lime. The presence of sulfites accelerates the cementitious reactions (Coltharp et al, 1979).

The stabilization reactions were found to depend on the as-produced water content of the sludge, the method of fly ash addition and the quantity of lime added which in turn affects the pH of the system.

The process requires the addition of fly ash and extensive dewatering of the sludge (Coltharp et al, 1979). As the as-produced water content of the sludge increases, a longer stabilization period and greater quantity of fly ash and lime are required to obtain the desirable results.

7.1.2 Properties of Stabilized Sludge

IUCS states that the Poz-O-Tec process results in a disposal product which is ecologically sound, economically feasible, and technically proven in full-scale power plant operations.

Figure 7-1 presents strength development of mixtures prepared by means of the IUCS Poz-O-Tec process used as the road base for a parking lot at the TRANSPO 72 (Minnick and Maneval 1974). The coefficients of permeability of these mixtures are shown in Table 7-1.

However, Coltharp et al, (1979) pointed out that some reported data for unconfined compressive strength had indicated that the engineering properties of the stabilized product were not significantly improved over those achievable by a simpler disposal treatment.

7.1.3 Case Histories

The use of the Poz-O-Tec process had been demonstrated in a number of sludge stabilization contracts as reported by the IU Conversion Systems and summarized in Table 7-2. It is applicable to the disposal of most of the waste materials generated by various FGD processes.

The stabilized sludge was also reported to have been demonstrated as a structurally stable landfill for supporting a condominium and as road base for highway and parking lots. It was also used as a pond liner for fly ash disposal at Arizona Public Service's Four Corners generating station and at the Chewick station in Pittsburgh (Coltharp et al 1979). Also, the Poz-O-Tec product was used for a highway embankment project in Pittsburgh.

7.2 Dravo Process Using Calcilox

7.2.1 Process Description

The Dravo process is based on the addition of Calcilox in dry or slurry form to stabilize the FGD sludges. Calcilox is a cementitious agent which is prepared by quenching blast furnace slag very rapidly and then pulverizing it to a specific size range. Dravo reports that adding Calcilox to the sludge would result in a disposal product which demonstrates low permeability, greatly improved leachate quality and structural stability (Coltharp et al, 1979).

In the Dravo process, the underflow containing calcium salts and excess reactant are combined in a mixing tank to which Calcilox is added. Lime may be added to optimize pH. The presence of fly ash is not a process requirement. After mixing, the treated sludge can be pumped to the final disposal site or to interim stabilization ponds where the stabilized material can be excavated and transported to a final disposal site.

The raw materials required are Calcilox and, in some cases, lime. The amount of Calcilox required ranged typically from 5% to 10% of dry slurry weight.

The operation of the process depends on the quantity of Calcilox, solids content of the as-produced sludge, curing temperature and pH.

7.2.2 Applicability of Dravo Process Technology

The Dravo process requires a large area of land for interim ponding if the option of interim stabilization and subsequent excavation is selected.

Since a large quantity of Calcilox is required for this process, the cost of transporting it may be considerably high.

7.2.3 Properties of Stabilized Sludge

Haynes et al, (1979) reported that Calcilox-stabilized sludges typically had unconfined compression strengths greater than 4.4 kg/cm2 (9000 psf) after 30 days curing time, a coefficient of permeability of 1×10^{-5} to 1×10^{-6} cm/s and a solids content of 40% to 50%.

7.2.4 Case Histories

The Dravo process using Calcilox as an additive had been claimed to be applicable to the stabilization of scrubber sludge slurries containing from 25% to 60% solids by weight (Coltharp et al 1979). The applicability of this process had been demonstrated by laboratory studies, pilot plant studies, and full scale operations as summarized in Table 7-3.

7.3 Chemfix Process

7.3.1 Process Description

The Chemfix process was developed to dispose of hazardous waste sludges such as metal hydroxides. It is based on a two-stage method to stabilize sludge mixtures and uses the reaction of sodium silicate and portland cement to accomplish stabilization. The reaction results initially in the formation of a gel-like material with water being contained in the gel. The final reaction is between the setting agent and the various components of the sludge which results in further stabilization, both chemically and physically (Haynes et al, 1979).

The raw materials required are sodium silicate and portland cement. In the unusual case where the pH is below 4, lime addition may be required. It was reported that the quantity of treatment chemicals required were below 5% by volume. The presence of fly ash is not a requirement.

The operation of the process depends on the solids content of the as-produced sludge and the pH. Stabilization is inhibited approximately 5% to 10% at temperatures below freezing.

7.3.2 Applicability of the Chemfix Process

The Chemfix process had only been demonstrated for a relatively low-volume waste disposal situation and more large-scale demonstrations may be required to verify the applicability of the process.

The use of portland cement and sodium silicate may render the cost of this process fairly high.

7.3.3 Properties of the Stabilized Sludge

Haynes et al, (1979) reported that the stabilized waste had a soil-like consistency. The unconfined compression strength and the coefficient of permeability ranged from 1.96 kg/cm2 to 15.7 kg/cm2 (4000 to 32,000 psf) and from 1 x 10^{-5} cm/s to 1 x 10^{-6} cm/s, respectively.

7.3.4 Case Histories

The Chemfix process has demonstrated the applicability of stabilizing mainly industrial wastes and its experience with FGD waste products has been limited to the EPA Shawnee field demonstration project.

In the Shawnee pilot plant demonstration, the sludge was pumped into a mobile van containing the chemical storage and the mixing equipment at flow rates of 300-500 gallons per minute. The treated sludge then required 24-72 hours set-up time under ambient temperature and pressure before it was excavated and trucked (Colthard et al, 1979).

7.4 Forced Oxidation

7.4.1 Process Description

Calcium sulfate is a more desirable waste product than calcium sulfite due to its improved ease of dewatering to greater than 80% solids content, its decreased volume of final waste products and the reduction of a thixotropic potential inherent in calcium sulfite sludge. It can be landfilled without the use of mixing equipment and fixation additives.

In the forced oxidation process, oxygen is introduced to oxidize the calcium sulfites in the sludge to calcium sulfates (gypsum), thus producing a more manageable waste product. Only 95 percent oxidation is necessary. The gypsum produced may be marketable depending on the availability and the demand of natural gypsum in the area concerned.

7.4.2 Properties of the Stabilized Sludge

Owing to the shape and size of the gypsum crystals, the gypsum-rich sludge can be dewatered to greater than 80% solids content by means of a centrifuge or a filter vacuum and can be disposed of by landfilling without further treatment.

Hagerty et al, (1977) reported that sulfate-rich sludge possessed superior dewatering properties and were more stable and less compressible than the sulfite-rich sludges.

7.4.3 Case Histories

Haynes et al, (1979) reported that calcium sulfite could be oxidized by air/slurry contact in the scrubber reaction tank. A simple one-loop forced oxidation system is shown in Figure 7-2. In this system, sulfite sludge is oxidized to gypsum in the oxidation tank by spraying with compressed air. Gypsum is dewatered by a thickener and vacuum filter to 80% solids. The final product is then transported for storage or landfilling.

CHAPTER 7

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TABLE 7-1

RESULTS OF TESTS OF SELECTED STABILIZED ROAD BASE MIXTURES PREPARED AT DULLES AIRPORT TRANSPO 72 PROJECT (MINNICK AND MANEVEL, 1974)

Moisture Content (%)	Dry Density (pcf)	Falling Head Permeabilities (cm/sec)	Compressive Strength at 100°F (psi)		
		7 Days	2 Days	14 Days	28 Days
19.5	98.8	2.4×10^{-6}	301	732	881
19.4	98.1	N.D.*	267	586	622
20.0	98.3	2.9×10^{-6}	369	630	889
19.8	98.2	6.5×10^{-6}	196	458	490
19.7	100.6	5.7×10^{-6}	333	772	861
20.0	98.8	1.0×10^{-6}	290	761	789
19.1	100.4	N.D.	200	868	1091

*N.D. - Not Determined

TABLE 7-2

FLUE GAS CLEANING WASTES DISPOSAL PROJECTS CONTRACTED BY I.U. CONVERSION SYSTEMS (COLTHARP ET AL, 1979)

CLIENT	STATION	MEGAWATT RATING	TOTAL WASTE DISPOSAL/YEAR	STATUS
Columbus & Southern Ohio Electric	Conesville 5 & 6	830	650,000	Completed summer 1976; not on line
Duquesne Light	Elrama	200	280,000	Completed tests Nov. 1, 1976
Duquesne Light	Elrama	500	700,000	Under construction
Duquesne Light	Phillips	400	450,000	Under construction
Indianapolis Power & Light	Petersburg	515	550,000	On line November 1977; landfill construction in progress
Southern California Edison	Mohave	180	65,000	Terminated after 2 years
EPA	Shawnee	10	Treated sludge for 24 days in 1975	

Source: IUCS, Personal communication, 18 January 1977.
Fling et al., 1976
Leo and Rossoff, 1976a

TABLE 7-3

FLUE GAS CLEANING WASTE DISPOSAL PROJECTS
CONTRACTED BY DRAVO CORPORATION
(COLTHARP ET AL, 1979)

CLIENT	STATION	MAGAWATT RATING	TONS OF SLUDGE DAY (WET BASIS)	STATUS
CAPCO[1]	Bruce Mansfield	917	21,000	Online since 1976
Duquesne Light	Phillips	400	750	2-1/2 yr. study completed Spring 1976
SCE	Mohave	150	N.R.[2]	Completed
West Virginia Utility	N.R.[2]	1236	5,500	618 MW online in 1979; Additional 618 MW online in 1980
EPA-TVA	Shawnee	10	N.R.[2]	Demonstration 1975 - present

[1] CAPCO - Central Area Power Coordination Group - Ohio Edison, Duquesne Light, Cleveland Electric, Toledo Edison, Pennsylvania Power Company.

[2] N.R. - Not reported.

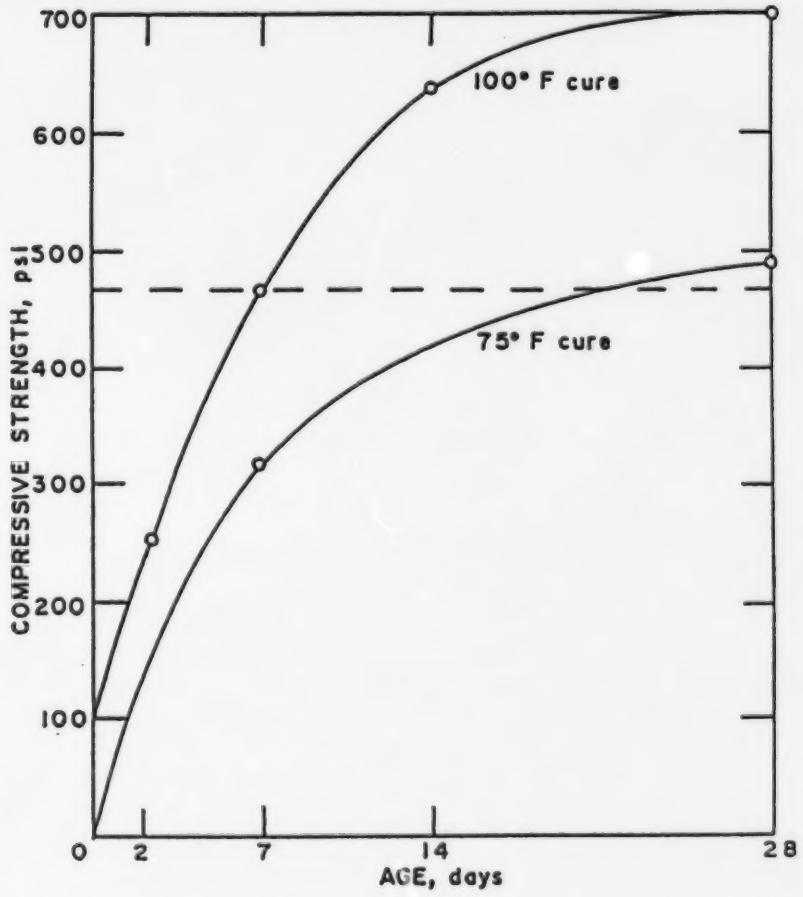

FIGURE 7-1

AVERAGE STRENGTH OF 26 LIME-SULFATE-FLY ASH-AGGREGATE MIXTURES (MINNICK & MANEVAL, 1974)

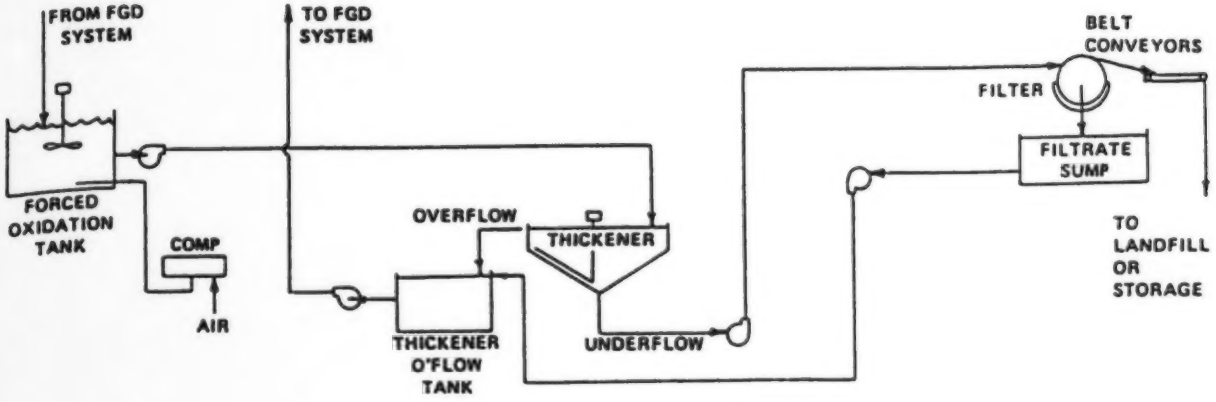

FIGURE 7-2

FORCED OXIDATION
(HAYNES ET AL, 1979)

8.0 UTILIZATION OPTIONS

Owing to the huge amount of FGD wastes produced from power plants using FGD technology to reduce the emission of sulfur dioxide gas, the potential of utilizing the wastes will be very desirable in reducing the long-term demand for off-site disposal space and, possibly, in providing additional revenue for the utility operators. A list of areas where studies have been made in various degrees for the utilization of the FGD sludges is presented below.

1. Commercial gypsum production;
2. Structural fill or roadbase;
3. Hazardous waste stabilization;
4. Cement additives;
5. Soil additives;
6. Waste disposal site liner;
7. Synthetic light-weight aggregates and bricks;
8. Manufacture of ceramic products;
9. Asphalt filler;
10. Grouting filler;
11. Recovery of sulfur.

It should be pointed out that many of the studies are only in the preliminary stage and so only the following important areas where comparatively detailed investigations have already been carried out will be discussed.

Commercial FGD Gypsum Production

Large quantities of hydrous calcium sulfate and calcium sulfite are generated as by-products from many FGD processes. In the forced oxidation system, the formation of the sulfate can be converted to gypsum which is a potential saleable products for use in making wallboard, as a setting retardant for cement and for use as fillers and additives in agricultural products.

The potential utilization of gypsum could help offset the operating cost and long-term liability associated with FGD waste disposal. However, due to the presence of impurities in the by-product gypsum, the utility operators may be required to provide additional processing on the by-products in order to meet the stringent requirements of the end users which may render the use of the by-product gypsum economically impractical. In addition, the cost of transporting the gypsum to various markets should also be taken into consideration.

Structural or Roadbase Fill

Minnick and Maneval (1974) reported the utilization of sulfite-rich FGD sludges and fly ash as a roadbase for a parking lot.

Taylor (1973) described some of the laboratory testing and field demonstration programs undertaken by the Combustion Engineer Inc. to show the feasibility of using FGD sludge for filling embankment and reclamation and for road construction. A typical scheme for producing suitable landfilling material is presented in Figure 8-1.

Ontario Hydro (1987) pointed out that there had been some interest expressed by municipal works representatives, contacted during their public involvement program, in using these materials for local road construction purposes. Further testing was expected to be necessary to fully prove the material for large-scale use.

However, the utilization of FGD sludge in this area is not expected to be significant enough to utilize all of the FGD waste produced at any one generating station. In addition, this option will be very sensitive to transportation planning needs and is unlikely to generate a constant demand for the sludge.

Hazardous Waste Stabilization

Research on stabilization of hazardous wastes with FGD waste have been in progress and the result is encouraging (Ontario Hydro, 1987). However, this option is unlikely to provide a significant consumption of FGD waste and is not expected to be of major value in reducing long-term disposal needs.

Cement Additives

A small amount of gypsum can be added to portland cement as a set retardant.

Cement is a heat fused mixture of numerous minerals including calcium carbonate, silica and alumina. The impurities in the by-product gypsum can react with other constituents in the cement and may cause durability problems in concrete if the mixing is not performed with due consideration.

Rush and Edwards, (1978) reported the preliminary test results on cement samples prepared by replacing natural gypsum with a sulfate-rich sludge. It was found that the FGD-cement performed similarly to ordinary cement at normal temperature. However, it caused the cement to set slower at colder temperature and required more FGD gypsum at higher temperature.

Soil Additive

Owing to its alkalinity and mineral content, FGD waste can act as a liming agent to neutralize soil acidity and as a soil fertilizer. By mixing it with a very fine grain soil, it can improve the moisture and conductivity of the soil and render healthier plant growth. When mixed with a sandy soil, it can improve the water retaining capacity of the soil.

However, the over abundance of some toxic elements and alkalinity of the waste and the possibility of creating a pozzolanic reaction in the soil render some restrictive use of this option unless extensive and long-term experimental

positive evidence is provided. For example, heavy metal concentration in the food chain is of particular concern since heavy metal accumulation in animal organs have been found to be the major cause of some metabolic disorders.

The high cost and the acquisition of land for the disposal of FGD wastes have resulted in an increased interest in utilization of the wastes as an alternative to the conventional landfilling disposal method. Numerous researchers have demonstrated that technology is available to take advantage of utilizing the wastes and experimental evidence is present to answer many queries from end users who still have doubts on the material. However, detailed economical studies should also be conducted in order to evaluate the marketability of the products.

CHAPTER 8

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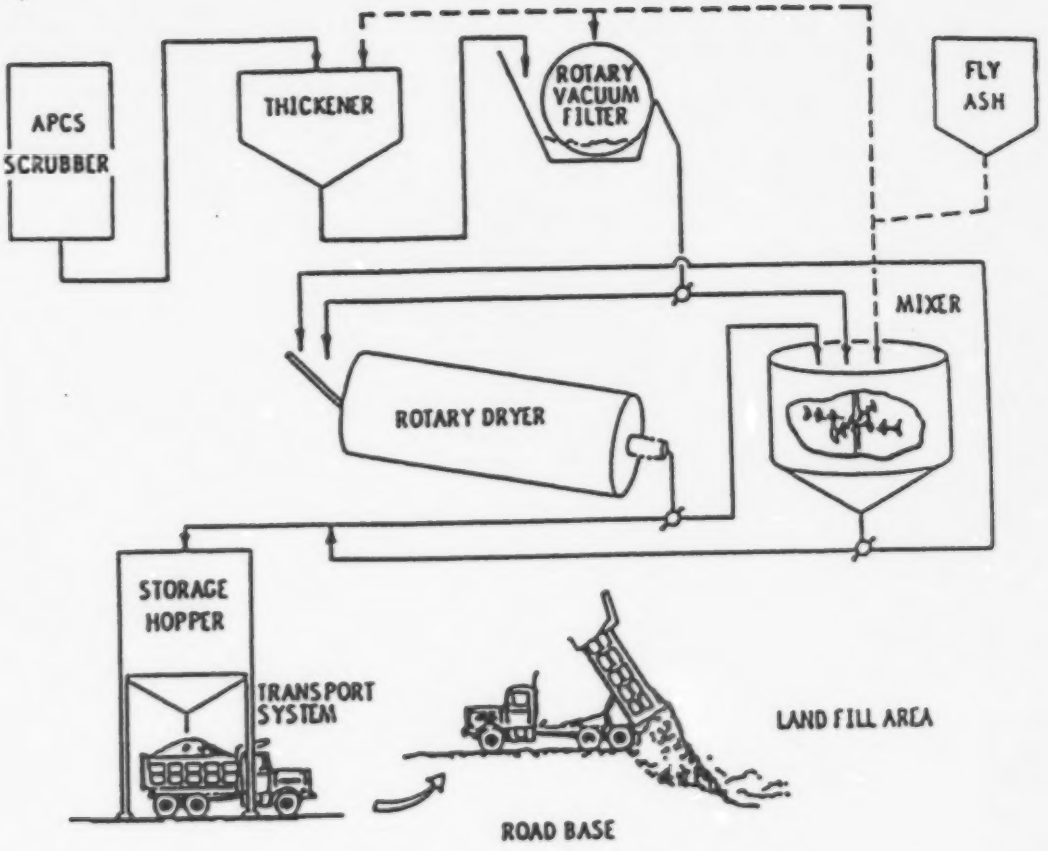

FIGURE 8-1

SCHEME FOR PRODUCING SUITABLE LAND FILL
(TAYLOR, 1973)

9.0 RECOMMENDATIONS FOR FUTURE RESEARCH

9.1 General

The engineering characteristics of the solid wastes generated by the limestone/lime dual alkali and limestone wet scrubbing processes have been described in previous chapters. However, owing to the variability of the FGD process, the properties of the FGD solid wastes vary significantly and the aforementioned properties can only serve as guidelines for planning the waste utilization, marketing and disposal strategies. The detailed implementation process should be designed for a specific type of FGD process, the quality of the coal and the type of absorbent employed.

9.2 Recommendations For Future Research

1) Long-term physical studies can be used to relate laboratory measured properties to long-term behaviour of the disposed sludge in the field. Some important aspects include:

Laboratory Studies	Field Behaviours
Consolidation	Settlement Total disposed volume
Permeability	Leachate rate
Compressive strength	Load bearing capacity Slope stability
Thixoptropy	Liquefaction

2. Long-term chemical studies and groundwater monitoring.

   Data are required to correlate the groundwater quality in the vicinity of FGD waste disposal sites to the waste characteristics and geological conditions of the site. The FGD waste characteristics include laboratory and field permeability, the volume of the waste and the chemical composition of the waste and leachate. The geological conditions include the extent of the affected area, the hydrological conditions of the site, the permeability of the subsoil and the liner and the location of the water table. The studies should aim to evaluate:

   1) theoretical basis for leaching of FGD wastes,
   2) in-situ leaching conditions,
   3) leachate characteristics of stabilized FGD wastes,
   4) models correlating laboratory leaching test results to field data.

3) Economic studies on utilization of FGD wastes

The potential utilizations of FGD wastes depend not only on the physical and chemical characteristics of the wastes, but also on the economic aspects of the potential application of the waste. The following studies should be made in evaluating potential application with respect to the local conditions.

1) Economic studies of the size and location of the market.
2) Value of the by-product compared to that of competitive products.
3) Cost of processing and the processing equipment.
4) Cost of transportation requirement.
5) Range of properties of the by-product acceptable to particular end users.

4) Biological action on the wastes

Coltharp et al, (1979) pointed out that occasional H_2S production had occurred under pilot scale operation, particularly when anaerobic conditions had existed. The release of this toxic gas may represent a potential problem associated with sludge disposal. Investigation should be conducted into the possibility of H_2S production by chemical and biological decomposition of FGD sludges.

CHAPTER 9

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